Improving conveyor weigher verification accuracy with reference weights without technological process shutdown

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Abstract. There are proposed the kinematic schemes of two-channel conveyor belt weighers which allow minimizing the errors of the verification using the reference weight without stoppage of the production process. There are presented two options of calculation of the reference weight mass simulating the bulk material taking into account the systematic and additional error of the conveyor belt weighers.

1. Introduction
Some of effective methods of improving the measurement accuracy are methods based on the use of test signals and information redundancy [1]. If there is no possibility of checking conveyor weigher (CW) with a weighed bulk material according to [2], it is proposed to verify the weigher with reference weights without the technological process shutdown [3], during which the material reproduces all uninformative factors inherent in the process of weighing a moving material along the conveyor belt, which increases the accuracy verification.

A feature of the CW as measuring devices for accounting for the bulk material transported by a belt conveyor is that they are not autonomous measuring devices and their accuracy depends largely on the parameters of a particular conveyor and belt, as well as on the nature of the bulk material flow.

2. Method
In the proposed verification method, the principle of the CW information redundancy assumes the presence of two channels for measuring the material mass, i.e. electrically and mechanically separate primary measuring transducers, load receptors (LR). The test effect on the CW is achieved by using reference weights, alternately loading directly each of the two main units in two-channel CW during verification with bypassing the conveyor belt.

In general, a larger number of measurement channels can be used in the CW scheme. In this case, it is advisable to represent multi-channel CW in the form of a certain combination of two-channel CW [4].

In work [3] there were considered the following possible verification errors:
1) the error of mutual interference of the measurement channels when alternately loading the weight roller supports of the LR with a reference weight;
2) the error due to the unevenness of the bulk material flow when measuring at the stages of verification;
3) the error of simulating the material flow with a reference weight when it is directly loaded on the LR with bypassing the conveyor belt;
4) the error in determining the simulated mass of the bulk material.

The mutual interference of the measurement channels during verification is caused by the fact that when the weight roller support of one of the load receptors is loaded with a reference weight, its additional drawdown occurs. This leads to the unloading action of the belt tension force on the given weight roller support. The adjacent weight roller support, not loaded with a reference weight, will experience additional loading from the belt tension force. Due to the effect of tension as an uninformative factor, the readings of the measurement channels counters change, which can be characterized by the error of mutual interference. This error is the error of approximation and is determined by the expression [3]:

\[ \delta_m = \frac{3\sigma}{cl_B - 3\sigma}, \quad (1) \]

where \( \sigma \) is the belt tension; \( c \) is the force sensor rigidity; \( l_B \) is the belt weight measuring section.

Expression (1) is valid for the model of a conveyor belt in the form of an inextensible elastic thread, which makes it possible to obtain a simple analytical dependence. However, this model does not allow taking into account the effect of the belt transverse rigidity and the features of its deformed state. In addition, it is difficult to determine accurately the force sensor rigidity and the belt tension in real production environments. In this regard, expression (1) cannot give the exact value of the error approximation for mutual interference.

The error of mutual interference of the measurement channels can be determined experimentally in the absence of the bulk material on the stationary conveyor belt. In [5], an expression for the error of approximation for mutual interference is presented as

\[ \delta_m = \frac{3\Delta R_2}{R_1 - \Delta R_2}, \quad (2) \]

where \( R_1 \) is the response of one LR with loading it with the reference weight expressed in the units of analog-digital converter (ADC); \( \Delta R_2 \) is changing the response of the underloaded with the reference weight LR expressed in the ADC codes.

However, expression (2) does not give the exact value of the error of mutual interference due to changing the belt tension at the place of mounting the CW when transporting the bulk material.

Since the operations to determine the error of mutual interference of the CW measuring channels are rather laborious and cannot give an unambiguously accurate value, the factor of mutual interference can be eliminated if the kinematic diagram of the CW is changed by separating the weight roller supports of the LR from each other with an intermediate stationary roller support. In fact, in the real conditions of mounting the load receptor on the line of the conveyor and taking into account the technological spread of their design dimensions between the measuring channels, residual mutual interference can appear, although to a lower extent. Therefore, the number of intermediate stationary rollers must be increased. For example, Figure 1 shows the options of implementing kinematic diagrams of two-channel CW with a single-roller and two-roller LR with the number of stationary intermediate roller supports equal to two. Similar diagrams can be presented for LR with three or more weight rollers.

In [3], the derivation of the analytical dependence for determining the permissible value of the reference weight the mass is presented based on the responses of the weight rollers of both LRs for the option when the weight rollers are not separated by an intermediate stationary roller support. In the case of separating the weight roller supports by stationary roller supports, as in Figure 1a, determining the reference weight mass can also be performed taking into account the graphical representation of the relationship between the physical quantities characterizing the process of interaction of each channel and the conveyor belt.
Figure 1. Kinematic diagrams of two-channel CW: 1-4 – stationary roller supports; LR1, LR2 – load receptors of the first and second measuring channels; DV – force measuring sensors. a) kinematic diagram of two-channel CW with a single-roller LR; b) kinematic diagram of two-channel CW with a double-roller LR.

The process of interaction of the conveyor belt with the CW when simulating a part of the real material with a reference weight, which loads directly the weight roller support, is shown in Figure 2.

For the option of full loading the belt with the material, when point C is the working point along the material on the straight line $G = f_1(y)$, the responses of the LR1 weight roller support:

$$R_G = G \frac{cl_B}{cl_B + 2\sigma},$$

where $G$ is the weight of the material on the weight section of the LR1 belt.

For the option of loading provided by the material part $G - P_g$ (the straight line $G' = f(y)$), the response of the LR1 weight roller support to reducing the material weight on the belt by the reference weight $P_g$ value

$$R_{(G-P_g)} = (G - P_g) \frac{cl_B}{cl_B + 2\sigma}.$$

The response of the LR1 weight roller bearing on the material without additional loading reference weight corresponds to point A at the intersection of straight lines $G' = f(y)$ and $R = \varphi(f)$. 

Figure 2. The CW and the conveyer belt interaction plot.

When the weight roller support is additionally loaded directly with the reference weight, its drawdown increases by the amount \( \Delta f = \frac{P_g}{c} \) and, together with the weight roller support, the belt with the material sinks, which causes an imbalance of the LR1 due to the unloading action of the belt tension force \( \sigma \). The response of the LR1 weight roller bearing in the material decreases and becomes equal to \( R_{1(G-P)} \), which corresponds to point B on the straight line \( G' = f(y) \).

The response of LR1 in case of partial imitation of the material with a reference weight, which additionally loads the weight roller support, will be determined by the following expression:

\[
R_i = R_{1(G-P)} + P_g = (G - P_g) \frac{cl_B}{cl_B + 2\sigma} + P_g (1 - \frac{2\sigma}{cl_B}).
\]  

(5)

In the CW kinematic diagram (Figure 1a) with reducing the LR1 response by the value, the response of each neighboring stationary roller supports increases by \( \frac{2\sigma P_g}{cl_B} \), and the LR2 weight roller support response will not change.

The absolute value of decreasing the response of the LR1 weight roller support as compared with the option of the full loading the belt with the material

\[
\Delta R = R_g - R_1 = P_g \frac{4\sigma^2}{cl_B (cl_B + 2\sigma)}.
\]

At this the relative error of the material imitation with the reference weight

\[
\delta_i = \Delta R \frac{R_g}{P_g} = \frac{2\sigma}{G \cdot \frac{2\sigma}{cl_B}^2}.
\]

(6)

Since \( \langle cl_B \rangle \sigma \), we can accept

\[
\frac{2\sigma}{cl_B} \approx \frac{2\sigma}{cl_B + 2\sigma}.
\]
The systematic error that is an error caused by the force measuring sensor drawdown on the material

\[ \delta_C = (R_G - Q) / Q = -2\sigma / (cl_B + 2\sigma). \]  

(7)

The CW systematic error with additional loading the LR with a weight is determined as

\[ \delta_C^* = (R_1 - G) / G = -\frac{2\sigma}{cl_B + 2\sigma} \cdot \left(1 + \frac{P_{TP}}{G} \cdot \frac{2\sigma}{cl_B} \right). \]  

(8)

At \( P_s = 0 \) we have \( \delta_C = \delta_C^* \). If we accept \( P_s / G = 0.3 \), then \( \delta_C^* = -1.004\delta_C \), i.e. the CW systematic error with additional loading the reference weight does not practically change.

Therefore, the relative error of the material simulation with a reference weight can be presented as

\[ \delta_i = \frac{\Delta R}{R_g} = \frac{P_s}{G} \cdot \delta_C^2. \]  

(9)

With the parameters typical for an industrial conveyor, \( \sigma = 10,000 \text{ N} \); \( l_B = 1.0 \text{ m} \); \( c = 3,000,000 \text{ N/m} \), the systematic error in accordance with expression (7) will be 0.006 (0.6 %). The minimum limiting error in determining the bulk material mass using a static scale is 0.1 % [7]. Taking the error of the material imitation by the reference weight \( \delta_i = 0.1 \% \), we obtain by (9) the ratio \( P_s / G = 0.3 \), i.e. the reference weight mass can reach 30 \% of the bulk material weight on the conveyor belt. At \( P_s / G < 0.3 \), the error of simulating the bulk weight flow by the reference weight will not exceed 0.1 \%. Therefore, in the proposed CW kinematic diagram with intermediate stationary roller supports, when assessing the total verification error, the error in simulating the weight flow with the reference weight when it is directly loaded with the load receptor can be ignored.

Separation of the weight roller supports of both single-roller LRs by intermediate stationary roller supports halves the weight section of the CW, which in turn leads to increasing the error component due to the inevitable inaccuracy of the mounting the weight roller supports relative to the neighboring stationary roller supports, with uneven flow of the bulk material [6].

This error for single-roller LRs is determined by the expression:

\[ \delta = -\frac{200\sigma}{cl_B + 2\sigma} \cdot \left(1 \pm \frac{h_0c}{ql_B \cos \beta}\right), \% \]

where \( h_0 \) is the equivalent weight roller support level displacement relative to the stationary roller supports; \( \beta \) is the belt angle.

The sign “+” is used with decreasing the level of setting the weight roller support, the sign “−” is used with exceeding the level of its setting.

Such an error possesses simultaneously some properties of both random and deterministic errors. At the same time, it refers to errors caused by the non-informative parameters.

In [5], there is formulated the condition under which it is possible to exclude the component of the verification error due to the uneven bulk material flow of when measuring at the verification stages, i.e., the so-called dynamic error caused by a possible change in the measured value. In this case, this value is the linear density of the bulk material. This condition requires the identity or sufficient proximity of the metrological characteristics of both LRs. These characteristics are the dependences of the errors of the measuring channels on the current value of the material linear density of the material \( \delta = f (q_M) \).

Due to a small length of the weighing section in a single-roller CW, the possible inaccuracy of setting the weight rollers relative to the neighboring stationary rollers, it is practically impossible to
achieve the identity conditions of the metrological characteristics. Therefore, it is recommended to use CW with a single-roller LR on conveyors with a constant, time-invariant bulk material flow, i.e. on conveyors with constant productivity when transporting the material. On conveyors with an uneven bulk material flow, two- and multi-roller LRs can be recommended for use.

Reducing the error in determining the bulk material mass simulated by the reference weight is also achieved by using two- and multi-roll LRs with an increased length of the weighing section of the belt.

When establishing the dependence for calculating the mass of the reference weight, the factor of ambiguity of the LR drawdown was taken into account when it was directly loaded with a standard load and increasing the material mass on the conveyor belt corresponding to this weight. However, there is another factor caused by the ambiguity of the CW relative error when weighing only the material and the material on the belt with the reference weight added directly to the LR, which does not reproduce the additional errors introduced only by the belt with the material.

Minimizing the effect of the second factor is achieved with differential accounting when weighing the material of individual components in the CW total relative error \( \delta_M \), which must be considered as consisting of two components:

1) systematic relative error due to the working drawdown of the load receptor under the action of the load;
2) additional relative error introduced by uninformative mechanical factors (disturbances) as resistance to the belt movement; its asymmetric deformation on inclined conveyors; dynamic loads, etc.

The additional error depends practically only on the value of the bulk material mass therefore, its effect on the total verification error \( \delta_H \) when the load receptor is additionally loaded with a reference weight should be determined taking into account the ratio of the bulk material mass and the reference weight.

In order to find the dependence for calculating the possible verification error and the rational ratio of the reference load and bulk material masses on the belt, we will take the following designations:

\[
A = \frac{\delta_C}{\delta_M},
\]

where \( A \) is the value characterizing the contribution in the total relative error of the CW measuring channel on the material of the systematic component caused by the LR working drawdown under the action of the material; \( \delta_C \) is the systematic component for the CW measuring channel total error; \( \delta_M \) is the total error of the CW measuring channel on the bulk material;

\[
B = \frac{Q_i}{Q_M},
\]

where \( B \) is the ratio of the calculated material mass \( Q_i \) simulated with the reference weight to the bulk material mass \( Q_M \) that is fixed by the measuring channel.

For CW, in which the weight roller supports are separated from each other by intermediate stationary roller supports, the systematic error of the measuring channel in accordance with (7) and (8) is constant both for the bulk material and when the LR is loaded with a reference weight. The additional error \( \delta_b \) depends only on the value of the bulk material mass therefore, its effect on the total verification error when the LR is additionally loaded with a reference weight will be determined taking into account the ratio of the material and the reference weight masses.

The error \( \delta^*_I \) of the CW measurement channel is determined by the dependence

\[
\delta^*_I = \frac{Q^* - Q_M - Q_i}{Q_i},
\]

(10)
where \( Q^* \) is the reading of the measuring channel with its reference weight additional loading.

When the LR is additionally loaded with a reference weight, the resulting readings of the measurement channel will be the sum of the readings on the bulk material and the readings on the reference load, i.e. \( Q^* = Q_M + Q_x \). Therefore, if the reference weight is considered as a part of the real load on the material, then in the readings of the measurement channel on the reference weight, it is necessary to take into account the effect of the systematic and additional errors. Then the readings of the measurement channel on the reference weight will be determined by the

\[
Q_r = BQ_M (1 - \delta_c - \delta_D^*) = BQ_M (1 - A\delta_M - \delta_D^* \cdot \frac{Q_M}{Q_M + BQ_M}) = \\
= BQ_M \left[ 1 - A\delta_M - (1 - A)\delta_M \cdot \frac{Q_M}{Q_M + BQ_M} \right].
\]

Using the previous designations, we will present dependence (10) by the expression

\[
\delta_M^* = \frac{Q_M (1 - \delta_M) + BQ_M \left[ 1 - A\delta_M - (1 - A)\delta_M \cdot \frac{Q_M}{Q_M + BQ_M} \right] - Q_M (1 - \delta_M) - BQ_M}{BQ_M}.
\]

After transformation we obtain

\[
\delta_I = -\delta_M \cdot \frac{AB + 1}{B + 1}. \tag{11}
\]

The criterion of the verification method accuracy is the magnitude of the discrepancy \( \delta_I = \delta_M - \delta_I^* \) between the CW errors obtained during verification by the material, \( \delta_M \) and by the indirect method, \( \delta_I^* \). Taking into account that the systematic error has a negative sign, expression (11) is represented in the form

\[
\frac{\delta_c \cdot AB + 1}{A \cdot B + 1} = \delta_M - \delta_I = \frac{\delta_c}{A} - \delta_I.
\]

Solving this expression relative to \( B \), we obtain

\[
B = \frac{A\delta_I}{\delta_c (1 - A) - A\delta_I}.
\]

The B value corresponding to the part of the bulk material load simulated by the reference weight must be calculated from the condition \( B = P_g \cdot (G - P_g) \), where \( G - P_g \) is the conveyor load at which the corresponding \( Q_M \) verification is performed.

After transformations

\[
\frac{P_g}{G} = \frac{\delta_I \cdot A}{\delta_c - 1 - A}. \tag{12}
\]

For various operating conditions, the CW value \( A \) can be in the range of (0.4-0.7). At \( \delta_I = 0.1 \% \) and \( \delta_C = 0.6 \% \), the ratio \( \frac{P_g}{G} = 0.10 - 0.35 \). When selecting the mass of the reference weight, the overestimated \( A \) value should be taken, which guarantees the required verification accuracy, and the
underestimated value leads to an increase in the verification error. However, in this case, the total load on the force-measuring sensor from the bulk material weight and the reference weight should not exceed the nominal value for the sensor.

Increasing the mass of the reference weight during verification makes it possible to increase the measurement channels sensitivity and the measurement results reproducibility, which leads to decreasing the standard deviation of the measurement results and reducing the verification time.

The verification error can be determined if, using the verification algorithm [3], based on the measurement results, the mass of the reference weight is calculated.

The weight mass \( m_{1I} \) based on the measurement results with additional loading the first LR with the reference weight is determined as

\[
m_{1I} = m_s / k_{1K},
\]

where \( k_{1K} \) is the coefficient of correction of the first measurement channel.

Similarly the weight mass \( m_{2I} \) based on the measurement results with additional loading the second LR with the reference weight is determined as

\[
m_{2I} = m_s / k_{2K},
\]

where \( k_{2K} \) is the coefficient of correction of the second measurement channel.

The weigher relative error will be determined by the expression

\[
\delta_p = \frac{\bar{m}_I - m_s}{m_s} \cdot 100\%,
\]

where \( \bar{m}_I = (m_{1I} + m_{2I})/2 \) is the average value of the reference weight mass calculated on the basis of the measurement results when performing verification;

\( m_s \) is the actual mass of the reference weight obtained on the basis of weighing on the standard balance for static weighing.

3. Results
The error of measuring the reference weight based on the verification results will be the error of measuring the bulk material mass using the CW.

4. Summary
The use of the proposed kinematic diagrams of two-channel CW when selecting the optimal value of the reference weight mass allows the scales being verified without the technological process shutdown in various operating conditions of the belt conveyors and ensures minimization of verification errors, which makes it possible to achieve the guaranteed accuracy of weighing the bulk material.

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