Studying the possibility of algorithmic compensation of temperature instrumental errors of string accelerometers as a composition of a strapdown inertial unit

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Abstract. The article is devoted to the study of temperature errors of the string accelerometer used as part of a strapdown inertial unit. One of the main tasks facing the development of string accelerometers is the problem of compensating temperature effects to eliminate the resulting errors. One of the methods to solve such problems is to provide compensation for changes in the parameters of the string accelerometer, to level the appearance of the instrumental error in measuring the acceleration in the output signal of the device. On the prepared bench base at Scientific and Production Association of Measuring Technology (AO NPO IT) for setting up and conducting experiments, a study of string accelerometers, which are part of the strapdown inertial unit, was carried out. The study consisted of collecting output information from the device during its temperature calibration. During the experiment, the strapdown inertial unit was oriented in space so that its measuring axes of the accelerometer channels were directed alternately vertically upward or vertically downward with a smooth temperature change. The data obtained were analyzed to determine the dependence of the change in the initial vibration frequency of the string accelerometer and the design parameter of the accelerometer on the temperature in the operating temperature range of the device. An assessment of the possible level of efficiency of algorithmic compensation for changes in the accelerometer parameters was also shown. The studies carried out have shown the possibility, due to the algorithmic compensation of the temperature instrumental errors of one-component string accelerometers, to provide the accuracy requirements for the linear acceleration sensor channel of the strapdown inertial unit device in the operating temperature range. In particular, the use of algorithmic compensation for the temperature error of the initial frequency of the accelerometer $f_0$ reduced the absolute value of the parameter change by more than two orders of magnitude, and the maximum value of the error in approximating the change in the design parameter $k$ from temperature is an order of magnitude less than the value before algorithmic compensation.

1. Introduction
Rocket and space technology is inconceivable without a modern navigation system that allows you to determine the exact position of the body in space at any time. The inertial navigation systems are capable for autonomous navigation in any environment. Their distinctive characteristic is their ability to work to external signal without any reference and the atmospheric condition or line of sight obstruction do not affect them and they are applicable in underground and underwater operation [1]. The principle of inertial navigation’s operation is based on Newton’s first and second law of motion. It measures the
vehicle acceleration in an inertial frame of reference, then integrates it due to time and after that transform it to the navigation frame. By this way, the attitude, velocity, and position differences in the navigation frame can be achieved [2]. Modern navigation systems use a number of different sensors to determine the position of a moving object. It is known that an independent navigation system can be created only on the basis of inertial sensors, one of which is an accelerometer. The accelerometers are used to measure the specific force and gyroscopes for the implementation of an inertial frame of reference. The accelerometers provide the sensor output, which plays an important role for positioning [3]. Factor that affect the accelerometer’s performance and accuracy are: bias uncertainty, scale factor stability and asymmetry and random and quantizer noise [4]. The accuracy of the strapdown inertial navigation system is mainly affected by the errors of the sensors [5]. One of the main factor, which affects the stability, accuracy and reliability of an inertial navigation systems is the temperature. The temperature variation of environment and heating in operating system cause the temperature of accelerometer and electric circles, which may vary the zero offset and scale factor of accelerometer. In practical applications, the temperature error cannot be removed due to the imprecise model of temperature [6].

Continuous development and active improvement of the elemental structure, including domestic electronic components, in recent years has led to the development of string accelerometers. The set of problems that arise during their development are the tasks of increasing the accuracy of measuring the acceleration primarily by reducing the temperature error, as well as simplifying the requirements for the choice of physical and mechanical properties of materials and the shape of parts that determine the string tension [7,8]. NPO IT has developed a strapdown inertial unit (SIU) for measuring the parameters of an aircraft's motion. The SIU device includes three fiber-optic gyroscopes, a three-axis accelerometer unit, a special calculator unit and a power supply unit. The device must ensure the transformation of the projections of the angular velocity vector and the apparent linear acceleration of the product. The three-axis block of accelerometers uses single-string (one-component) sensitive elements of accelerometers developed by the All-Russian Scientific Research Institute of Technical Physics (VNIITF) named after academician E.I. Zababakhina, Snezhinsk [9]. Authors in [6] proposed an efficient temperature model by analyzing the temperature characteristics of accelerometer and verifying the compensation effect through experiments. The proposed model is more suitable in environment and can be applied for complex temperature conditions. Xiao et al. [7] used the idea of the Ramp method and suggested an improved thermal calibration method while investigating the thermal drift of a full set of accelerometer errors. As a result, they improved the calibration accuracy and efficiency. Qingjiang et al. [10] established the final thermal models and mitigated the accelerometer errors by using the sensor data during heat-and-stay and cool-and-stay processes.

This paper proposes an algorithmic compensation to measure the temperature error of the initial frequency of the accelerometer. Application of the new algorithmic compensation reduced the absolute value of the parameter change. During experiment the output data of the device during its temperature calibration were collected. By using the collected information the relationship between the change in the initial vibration frequency of the string accelerometer and the design parameter of the accelerometer on the temperature in the operating temperature range of the device was established. Finally the efficiency of algorithmic compensation for changes in the accelerometer parameters was verified.

2. Materials and methods

2.1. String Accelerometer Specifications

The peculiarity of the string accelerometer is the absence of a movable inertial mass, and the very principle of generating the output signal is based on the dependence of the frequency of transverse vibrations of a stretched string on their tension force, which in turn depends on the acting linear acceleration. In addition to the string element itself, the accelerometer includes an information pickup device, and the string excitation device was developed by NPO IT.

The dependence of the current oscillation frequency of the resonator of the string accelerometer on the acceleration is described by the well-known equation:
\[ f_x = f_0 \sqrt{1 + k \cdot a} \]  

(1)

Where:
- \( f_x \) – current frequency of string vibration, Hz;
- \( f_0 \) – the initial frequency of the frequency sensor, Hz;
- \( k \) – design parameter depending on string stiffness, s²/m;
- \( a \) – effective acceleration, m/s².

The parameter, independent of the measured value, is the initial frequency of the string pickup \( f_0 \), which is proportional to the typical parameter for linear accelerometers - the error of the “zero” signal \( \Delta a_n \).

As an analogue of the scale factor (conversion factor) of the linear acceleration accelerometer, we can take the design parameter \( k \) \([11,12]\).

If we express the acceleration from equation (1), then we obtain the measurement equation for the string accelerometer:

\[ a_{musr} = \frac{1}{k} \left( \frac{f_x^2}{f_0^2} - 1 \right) \]  

(2)

As follows from equation (2), the calculated value of the linear acceleration depends nonlinearly on the measured parameter - the current frequency of the string vibration.

A two-string differential accelerometer is used to linearize the measurement equation. However, the mass of two-string sensing elements (SE) of accelerometers exceeds the mass of single-string sensing elements, and the requirement to SE for the same parameters \( f_0 \) and \( k \) significantly increases the cost of sensitive elements. The use of a microprocessor in the SIU makes it possible to neutralize the negative properties of one-component string converters \([13]\). In the SIU for measuring linear acceleration, a specialized channel of the linear acceleration sensor (LAS) is formed, which, in addition to the sensitive elements of the string accelerometers, the electronics unit for the excitation of the string, includes a signal processing path for accelerometers. Accelerometer signal processing path includes synchronization circuits and two frequency counters: accelerometer frequency counter and filling frequency counter. A thermal sensor is installed on each sensitive element of the accelerometer, the signal from which is processed by the SIU microprocessor \([14-16]\).

Taking into account the implementation of the channel of the LAS, the measurement equation for the string accelerometer has the form:

\[ a = \frac{1}{k} \left( \frac{(n_x)^2}{(n_z)^2} \cdot \frac{f_x^2}{f_0^2} - 1 \right) \]  

(3)

Where:
- \( n_x \) – the value of the code read from the LAS frequency counter;
- \( n_z \) – value of the code read from the filling frequency counter;
- \( f_x \) – filling frequency, which should be two to three orders of magnitude greater than the initial frequency \( f_0 \);
- \( f_0 \) – effective acceleration, m/s²;
- \( k \) – design parameter depending on string stiffness, s²/m;
- \( a \) – effective acceleration, m/s².

The parameters \( f_0 \) and \( k \) must be determined during the calibration process and it is known that their values depend on temperature \([17]\). Consequently, the absence of compensation for temperature changes in the parameters \( f_0 \) and \( k \) will lead to the appearance of an instrumental error in measuring the acceleration in the output signal of the device.
2.2. Investigating Algorithmic Compensation in Temperature Calibration

In the course of the research, the following tasks were considered:

a) selection of modes for temperature calibration of LAS channels;

b) study of the repeatability of the temperature dependence of the measured parameters \(f_0\) and \(k\);

c) determination of the magnitude of the change in the measured parameters in the operating temperature range;

d) assessment of the possible level of efficiency of algorithmic compensation for changes in parameters \(f_0\) and \(k\).

These studies were carried out on a specialized setup previously created at NPO IT, which includes an adjustable heat chamber and a two-axis swivel rotary table for rotation and positioning installed in it.

Taking into account the required operating mode of the SIU (duration of operation 600 s.), the following modes of calibration were selected:

a) in the operating temperature range, a constant rate of temperature change over time was set;

b) during the calibration, the instrument was periodically turned off for 1 minute, and then one measurement was performed: the instrument was turned on for 10 minutes, during which the values of the parameters \(f_0\) and \(k\) were measured;

c) the set rate of temperature change made it possible to ensure the temperature change in one measurement by no more than 1° C.

Methods of measuring the parameters \(k\) and \(f_0\) in the operating temperature range was carried out using equation (1) by applying the well-known method for measuring the output signals of the accelerometer at four orientations of its sensitivity axis relative to the direction of the vector \(g\).

For convenience of further consideration, the following notation is used:

- \(R_x^0\) - measurement results of the parameter of \(R_x\) when the accelerometer sensitivity axis is oriented vertically upward;

- \(R_x^{90}\) - measurement results of the parameter of \(R_x\) with the orientation of the accelerometer sensitivity axis located in the horizon plane;

- \(R_x^{180}\) - measurement results of the parameter of \(R_x\) when the axis of sensitivity of the accelerometer is oriented vertically downward;

- \(R_x^{270}\) - measurement results of the parameter of \(R_x\) with the orientation of the axis of sensitivity located in the plane of the horizon.

The first step for the implementation of algorithmic compensation for changes in the instrumental errors of the LAS channel from temperature was to measure these errors in the operating temperature range. For this purpose, the test object was installed on a biaxial swivel setup, which, in turn, was placed in a specialized heat chamber. The position of the setup axes was fixed:

- the outer axis of the setup in the plane of the horizon;

- the inner axis of the setup is perpendicular to the horizon plane.

The location of the instrument axes of the test object relative to the cardinal points was also fixed:

- the \(X\) axis was located vertically upward;

- the \(Y\) axis was directed to the North;

- the \(Z\) axis was located orthogonal to the \(Y\) axis and supplemented the coordinate system to the right.

Based on the results of studies of the conditions of measuring the instrumental errors of the information management system channels in the operating temperature range, the measurement of the instrumental errors of the LAS channel was carried out in only one measurement condition: continuous temperature change from minus 16°C to 50°C when the LAS channel was turned on/off, the output signal recorded by channel information management system was carried out within 200 sec. after 60 sec. after power supply (time of test object readiness 60 sec.).

An important issue in the study of the possibility of algorithmic compensation for instrumental errors of the LAS channel was the experimental confirmation of the repeatability of changes in the instrumental
errors of the LAS channel in the investigated temperature range for different implementations. For this purpose, three test cycles were carried out.

In each test cycle, a continuous change in the temperature inside the heat chamber was set from minus 16°C to 50°C. During one activation of the test object, the four orientations of the sensitivity axis of the accelerometers indicated above were implemented.

In the course of one measurement, two orientations of the measuring axis of the studied channel of accelerometers were realized: the measuring axis of the accelerometer was located vertically upward, and the measuring axis of the accelerometer was located vertically downward with a smooth change in temperature inside thermal chambers [18-23]. These orientations correspond to the following measurement equations:

\[ R_X^B(T) = \frac{f_x}{f_0(T)} \sqrt{1 + k(T)} \cdot g; \quad R_X^B = \frac{n_X^B}{n_Y^B} \]  
\[ R_X^{NZ}(T) = \frac{f_x}{f_0(T)} \sqrt{1 - k(T)} \cdot g; \quad R_X^{NZ} = \frac{n_X^{NZ}}{n_Y^{NZ}} \]  

Where:
- \( n_X^B \) and \( n_Y^B \) – the value of the code read from the LAS frequency counter when the measuring axis is oriented vertically up and vertically down, respectively;
- \( n_X^{NZ} \) and \( n_Y^{NZ} \) – the value of the code read from the filling frequency counter when the measuring axis is oriented vertically up and vertically down, respectively;
- \( T \) – the temperature of the SE of the accelerometer;
- \( g \) – the acceleration of gravity.

In the field of one g, equations (4) and (5) can be simplified by using a series expansion of the function under the square root and taking into account only the first two terms of the series. Then the calculation equations for calculating the parameters \( f_0 \) and \( k \) from measurements in two orientations of the accelerometer are as follows:

\[ f_0(T) = \frac{(R_X^B(T) + R_X^{NZ}(T))f_x}{2}; \]  
\[ K(T) = \frac{(n_X^B(T) - n_X^{NZ}(T))f_x}{f_0(T)} \cdot g \]  

3. Result and discussion
In the course of the experiment, we studied the change in the initial oscillation frequency of the string accelerometer \( f_0 \) and the design parameter \( k \) in the operating temperature range of the device (the temperature of the accelerometer sensor). Data sets were obtained in three test cycles at a specialized set-up. Figures 1 and 2 show the graphs of changes in the initial vibration frequency of the string accelerometer \( f_0 \) and the design parameter \( k \) in the operating temperature range (temperature of the accelerometer sensor), obtained in three test cycles. As can be seen from the graphs, these dependences have good repeatability, which allows us to conclude about the deterministic nature of changes in these parameters with respect to temperature.

The change in the value of the parameter \( f_0 \) in the investigated temperature range of the device corresponds to the error of the zero signal \( \sim 5.4 \text{ m/s}^2 \), and the change in the value of the parameter \( k \) in the same temperature range was \( \sim 1.34\% \).

The primary processing of the information received was carried out in the MathCAD. The analysis of the graphs on the above graphs (Figure 1 and 2) showed that approximating analytical functions in the form of polynomials of the third or fourth orders are most applicable for them, the coefficients of which are calculated using regression analysis. At the same time, in the process of selecting functions, the investigated temperature range was divided into several intervals, within which the parameters of the approximating functions were calculated.

Equations of approximating functions for parameters \( f_0 \) and \( k \):
\begin{align*}
R(T) &= Q_0 + Q_1 T + Q_2 T^2 + Q_3 T^3 + Q_4 T^4 \\
S(T) &= P_0 + P_1 T + P_2 T^2 + P_3 T^3 + P_4 T^4
\end{align*}

(8)  
(9)

Tables 1 and 2 show the values of the coefficients of the polynomials of the approximating functions in different temperature ranges.

Figure 1. Change in the initial oscillation frequency of the string accelerometer $f_0$ in the operating temperature range in three test cycles

Figure 2. The graph of changes in the design parameter $k$ in the operating temperature range in three test cycles

The verification of the obtained approximating functional dependences of the coefficients of the polynomials of the approximating functions $f_0$ in different temperature intervals was carried out by a calculation method, which was implemented using the following expression:

\[
\Delta f_0(T) = f_0(T) - R_0(T) \quad \Delta B_0(T) = \frac{\Delta f_0(T)}{\kappa_{\text{acc}}}
\]  
(10)
where,

\[ \Delta f_0(T) \] – the error in algorithmic compensation for changes in frequency \( f_0 \) in the operating temperature range;

\[ f_0(T) \] – the value of the frequency \( f_0 \) calculated from the experimental data at the accelerometer temperature \( T \);

\[ R_0(T) \] – the value of the polynomial function, calculated for the temperature of the accelerometer \( T \) (the function was obtained by approximating the experimental data on the change in the initial vibration frequency of the string accelerometer \( f_0 \) in the operating temperature range);

\[ \Delta B_0(T) \] – the error of the “zero” signal of the accelerometer corresponding to the error of algorithmic compensation for the change in frequency \( f_0 \) in the operating temperature range;

\( K_{acc} \) – the conversion factor of the change in the vibration frequency of the accelerometer into acceleration, \( K_{acc} \approx 2.04 \text{ Hz/m/s}^2 \) (determined by the characteristics of the accelerometer).

**Table 1.** The values of the coefficients of the polynomials of the approximating functions \( f_0 \) in different temperature intervals

| Temperature range of polynomial coefficients | \( Q_0, Hz \) | \( Q_1, Hz/°C \) | \( Q_2, Hz/(°C)^2 \) | \( Q_3, Hz/(°C)^3 \) | \( Q_4, Hz/(°C)^4 \) |
|---------------------------------------------|-------------|----------------|-----------------|----------------|----------------|
| From -15°C to 7°C                           | 34497.28340 | 0.373651       | -2.0527x10^3    | 1.1665x10^3    | 6.8554x10^3   |
| From 7°C to 25°C                            | 34497.88939 | -0.472003      | 0.0115          | 7.8396x10^5    | 0.0           |
| From 25°C to 55°C                           | 34449.55157 | 4.4677         | -0.1570         | 2.3232x10^3    | -1.2617x10^5  |

**Table 2.** The values of the coefficients of the polynomials of the approximating functions \( k \) in different temperature intervals

| Temperature range of polynomial coefficients | \( P_0, Hz \) | \( P_1, s^2/m/°C \) | \( P_2, s^2/m/(°C)^2 \) | \( P_3, s^2/m/(°C)^3 \) | \( P_4, s^2/m/(°C)^4 \) |
|---------------------------------------------|-------------|-----------------|-----------------|----------------|----------------|
| From -15°C to 7°C                           | 1.243512x10^4 | -6.0831x10^-8  | -9.3242x10^-8   | 2.3059x10^-10 | 3.0867x10^-12 |
| From 7°C to 25°C                            | 1.759942x10^4 | -9.5423x10^-6  | 6.3062x10^-7    | -1.7583x10^-8 | 1.7543x10^-10 |
| From 25°C to 55°C                           | 1.502294x10^4 | -2.4662x10^-6  | 8.7800x10^-8    | -1.3685x10^-9 | 7.8194x10^-12 |

Figure 3 (a) show the results of verification of algorithmic compensation for changes in the initial frequency of the accelerometer \( f_0 \) in the operating temperature range using the obtained approximating functions in the form of compensation errors. It follows from Figure 3 (a) that the efficiency of application of algorithmic compensation for changes in the initial vibration frequency of the string accelerometer \( f_0 \) according to the obtained polynomial approximating functions is quite high. It is difficult to distinguish the signal component (signal trend) that slowly changes with temperature, the
The absolute value of the signal decreased by more than two orders of magnitude (from the equivalent error of the "zero" signal of accelerometers ~ 5.4 m/s² to ~ 0.06 m/s²), so that the nature of signal changes is close to a random process.

The verification of the obtained approximating functional dependences of the coefficients of the polynomials of the approximating functions $k$ in different temperature intervals was carried out by the calculation method, which was implemented using the following expression:

$$\Delta k(T) = \frac{(k(T) - S(T)) \cdot 100}{k(T)}$$

where,
- $\Delta k(T)$ – the relative error in the approximation of the change in the coefficient proportional to the elasticity of the accelerometer string in temperature;
- $k(T)$ – value of the coefficient "$k$" obtained at the temperature of the accelerometer $T$;
- $S(T)$ – the value of the approximating polynomial function obtained by the method of regression analysis.

Figure 3 (b) shows the results of verification of algorithmic compensation for changes in the design parameter $k$ in the operating temperature range using the obtained approximating functions in the form of compensation errors. It follows from Figure 3 (b) that the efficiency of applying algorithmic compensation for the change in the coefficient $k$, which is proportional to the elasticity of the accelerometer string, and the obtained polynomial approximating functions, is quite high. It is difficult to distinguish a component of the error (trend) that slowly changes with temperature, so that the nature of the changes in the error is close to a random process. The maximum value of the approximation error for the change in the coefficient "$k$" from temperature was ~ 0.15%.

**Figure 3.** (a) Compensation error for the change in the initial vibration frequency of the string accelerometer $f_0$. (b) Design parameter compensation error $k$

### 4. Conclusion

In this paper the temperature error of the initial frequency of the accelerometer $f_0$ has been measured applying the algorithmic compensation. The use of algorithmic compensation for the temperature error of the initial frequency of the accelerometer $f_0$ reduced the absolute value of the parameter change by more than two orders of magnitude (from the equivalent error of the "zero" signal of accelerometers ~ 5.4 m/s² to ~ 0.06 m/s²). The maximum value of the error in approximating the change in the design parameter $k$ from temperature was ~ 0.15%, which is almost an order of magnitude less than the value before algorithmic compensation.
In general, the studies have shown the possibility, due to the algorithmic compensation of the temperature instrumental errors of one-component string accelerometers, to provide the accuracy requirements for the LAS channel of the SIU device in the operating temperature range. One of the ways to further improve the efficiency of algorithmic compensation for instrumental errors of string accelerometers in the operating temperature range is to reduce the value of the temperature change per measurement of the parameter to (0.5 - 0.3){\degree}C, especially at negative temperatures.

Further suggestions to increase the efficiency of algorithmic compensation for the change in the coefficient $k$, which is proportional to the elasticity of the accelerometer string, in the operating temperature range, are:

- decrease in hardware sensitivity to temperature of the coefficient $k$ of the accelerometer;
- decrease in the value of the temperature change in one measurement of the parameter to (0.5-0.3){\degree}C (in these studies, the step of temperature change was from 5{\degree}C (at negative temperatures) to 1{\degree}C);
- application of the results of several measurement cycles (from 3 to 5) of the coefficient $k$ in the operating temperature range.

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