Modelling of Thermal Effects on Aerospace Devices and Their Components

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Abstract. Thermal effects on aerospace devices (sensors and systems) directly affect their performance. Thermal influences are one of the main sources of sensor's errors. The study of the effect of the thermal influences on the devices should be carried out for each device at the design stage. This work is especially crucial for high-precision devices or devices intended to be used in hostile environments like space. The paper proposes a classification and mathematical expressions of temperature influences that affect different kinds of aerospace devices and their electronic components during their operation. The algorithms developed by the authors allow modelling, for example, the change in the ambient temperature of components of a spacecraft navigation system when it is moving in circular or elliptical orbits, to simulate a cyclogram or stochastic of a temperature changing. The usage of the suggested types of thermal influences and relevant mathematical models can help to reduce the development costs of software for modelling and studying thermal processes in different classes of aerospace devices and speed up the process of its development.

1. Introduction
Thermal effects are one of the factors that have a significant impact on the accuracy and stability of sensors and systems [1-14]. Such influences can be critical for inertial devices (sensors, units, systems) used in hostile conditions, for example, in outer space. Therefore, the study of the influence of various thermal effects on such devices should be carried out at the stage of their design. Moreover, all the disturbing temperature factors which can arise in real operating conditions of the device should be taken into account for adequate numerical simulation of thermal processes in it.
This work aims to classify and to formulate the mathematical expressions of the temperature influences which can be during the operation of various kind of aerospace devices, sensors, and electronic components.

2. The main types of thermal effects
The disturbing thermal effects which can be during the operation of the devices in various environmental conditions can be divided into six types:

2.1. Constant
The thermal influence can be described by the following law (Figure1a):

\[ T_s(t) = \text{const.} \]  

(1)
2.2. Stepped
The temperature abruptly changes from \( T_{c1} \) to \( T_{c2} \) at the given time \( t_i \) (Figure 1b):

\[
T_e(t) = \begin{cases} 
T_{c1}, & t \in [t_0, t_i] \\
T_{c2}, & t \in (t_i, t_n]
\end{cases}
\] (2)

2.3. Harmonic
The mathematical expression of this kind of thermal influence (Figure 1c):

\[
T_e(t) = \frac{1}{2} \left( T_{e\text{max}} - T_{e\text{min}} \right) \sin(\omega t) + \frac{1}{2} \left( T_{e\text{max}} + T_{e\text{min}} \right),
\] (3)

where \( T_{e\text{max}} \) and \( T_{e\text{min}} \) - maximum and minimum values of temperature accordingly.

Such law of temperature changes can be used for imitation, for example, a change in the ambient temperature of the elements of the navigation system of a spacecraft in a circular orbit.

2.4. Cyclogram
Thermal influence is changed according to defined thermal cyclogram (Figure 1d):

\[
T_e(t) = (T_{e,i+1} - T_{e,i}) \frac{t - t_{i-1}}{t_i - t_{i-1}} + T_{e,i}, \quad i = 1..n,
\] (4)

where \( i \) - cycle number; \( T_{e,i} \) - temperature value in \( i \)-th cycle; \( t_i \) - \( i \)-th cycle start time.

The proposed law \( T_e(t) \) allows simulating any cyclogram of a temperature change. This law of temperature influence is used, for example, for temperature specifying in tests of the devices and their components in a heat chamber. An example of using this law is shown in Figure 2. There are the numerical simulation results, and experimental data of temperature changing in a fiber-optic gyroscope as part of a strapdown inertial navigation system placed in a heat chamber is shown in Figure 2.

2.5. Stochastic
Thermal influence is changed randomly. In this case, the mathematical law of temperature can be defined as follows (Figure 1e).

\[
T_e = M + \sigma \left( \left( a_5 r^2 + a_4 \right) r^2 + a_3 \right) r^2 + a_1, \quad r = \frac{\sum_{i=1}^{12} \delta_i - 6}{4},
\] (5)

where \( M \) - the mean; \( \sigma \) - standard deviation; \( a_1, a_3, a_5, a_7, a_9 \) - weight coefficient, \( \delta_i \in [0,1] \) - random function.

![Figure 1. Types of thermal influence:
2 - constant; b – stepped; c – harmonic; d – cyclogram; e – stochastic; f – free](image-url)
2.6. Free
If thermal influence cannot be defined by any of expressions (1)-(6) or their combination, it should be described manually by investigators. It can be any function or series (Figure 1f):

\[ T_e = f(t), \]

where \( f(t) \) - linear, exponential or another kind of functions of time dependence \( f(t) : \)

\[ f(t) = at + b \] или \( f(t) = A(1 - e^{-bt}) , \]

where \( a, b \) - some constant parameters.

![Figure 2. Current temperatures in SINS gyroscopes when modelling thermal processes: 1 - experiments data; 2 - simulation result; \( T_c \) - thermal influence](image)

Expressions (1) - (6) are algorithms for modelling of various types of thermal influence. These expressions can be used in the development of software for modelling the influence of thermal effects on the object under study.

3. Algorithms for thermal influence simulation
Formulas (1) - (7) can be used as continuous functions or discrete sets of values in multi-purpose simulation software packages (for example, ANSYS, Code-Aster, MATLAB, etc.), as well as in specialized developed software and libraries for specifying the functions of thermal effects on the object or its structural elements.

The specialised software for thermal effects modelling can be developed with taken into account formulas (1)-(7) and based on the modified heat balance method (TEB).

TEB is a numerical method which looks very similar to the finite element method. So, the model is subdividing into smaller parts – thermal elements. The elements can contain sources and(or) sinks of heat. They can connect to other elements and the environment. The environment can have a temperature that varies according to some law.

The primary system of equations in TEB has the form [1,2]:

\[ T_i(t + \Delta t) = \left[ 1 - \frac{\Delta t}{c_i} \left( \sum_{j=1}^{N} q_{ij} + q_{ie} \right) \right] T_i + \frac{\Delta t}{c_i} \left( \sum_{j=1}^{N} q_{ij}T_j + q_{ie}T_{ei} + Q_i \right), \]

where \( T_i(t) , T_i(t + \Delta t) (i = 1,\ldots,M) \) – the temperature of the \( i \)-th thermal element at time moment \( t \) and next moment \( t + \Delta t \); \( c_i \) - heat capacity of the \( i \)-th thermal element; \( q_{ij} \) - characteristic of thermal connection between \( i \)-th and \( j \)-th thermal element \( (j=1,\ldots,N) \); \( q_{ie} \) - characteristic of thermal connection between \( i \)-th thermal element and the environment; \( T_{ei} \) – ambient temperature; \( Q_i \) – power of source of heat or drain; \( M \) – total amount of TE in the model; \( N \) – amount of thermal element, which has thermal contact with \( i \)-th thermal element; \( \Delta t \) – calculation step.
The parameter $c_iT$ in (8) is a function of time and should be defined by one of the expressions (1)-(7) or their combinations.

4. Software and numerical simulation
An example of the developed software for studying the effect of thermal influence on the angular velocity measuring unit with fibre-optic gyroscopes is shown in Figure 3

![Figure 3](image)

**Figure 3** Specialized software for studying the effect of thermal influence

Numerical experiments have shown the sufficiency of the formulated types of thermal effects for modelling various temperature perturbations on the object under study.

5. Conclusion
The main types of thermal influences and the mathematical expression for them were formulated. These mathematical expressions can be used for numerical simulation and study of non-uniform non-stationary three-dimensional temperature fields with the help of well-known multipurpose or special software.

The suggested algorithms are adapted and ready for implementation in specialised or multipurpose software. So these algorithms can imitate various parameters of thermal effects, as well as other parameters of the ambient environment. For example, a change in the ambient temperature of the elements of the navigation system placed into a spacecraft can be simulated by the harmonic law when a spacecraft is moving in a circular or elliptical orbit, and by cyclogram in case of more complicated motion of the spacecraft. The parameters, such as weightlessness and vacuum, can also be taken into account.

The usage of the suggested types of thermal influences and relevant mathematical models can help to reduce development costs and speed up the process of development of software for modelling and studying thermal processes in different classes of aerospace devices.

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