Transient thermal contact in gyro unit–platform assembly

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Abstract. Thermal contact conditions of parts change in time in the process of heating. Cases of thermal contact instability may occur even under constant boundary conditions. This is due to the combination of temperature and strain fields interdependence based on thermal expansion, the influence of shape of parts and the conditions of their connection in the assembly. In this paper, using the example of a model problem of thermal contact of a gyro unit–platform assembly, we study qualitative and quantitative aspects of the temporal behavior of thermal contact conductance. A significant qualitative difference between thermal contact conductance and its steady-state value has been obtained. Given that the magnitude of the deviation is within the acceptable engineering accuracy, it is of interest in terms of thermal contact model development.

1. Introduction
Heating leads to spatial thermal expansion of parts. This expansion in combination with the constraints of connections in the assembled structure leads to increased stresses and additional deformation. Thus, both tightening and gapping of contacting parts are possible. There are possible contact options, when the thermal contact conductance does not reach its steady-state value for a long time or even never reaches one if it has an oscillatory character. This is possible if thermal expansion makes the contact open. For example, the controlled process of mechanical contact opening can be seen in widespread constructions of thermostats and thermoregulators. Figure 1 shows possible simplified construction of systems, where the transient process may fluctuate.

Figure 1. An example of thermal expansion leading to contact opening. \( t_0 \) is the shape of the body at the initial temperature, \( t_1 \) is the deformed warmed body with the open contact: a) the contact opening upon buckling due to thermal expansion; b) opening due to the deformation of the samples in the thermal contact conductance measurement test.
In real structures of complex shape there will be an intricate and often unpredictable surface warp, also influenced by dependence on heat fluxes and compliance resulting from the asperity deformation. Such a warp should be taken into account by solving transient problems with finite element models. The temporal change in contact conditions leads to the change in thermal contact conductance. This changes the temperature field, which in its turn has an impact on thermal contact conductance as well. The latter, apparently, can explain the significant change in the measured dependence of thermal contact conductance on the strain rate during hot forging of metal described in [1]. Faster loading forms different temperature fields of the billet and the die and, therefore, changes the contact thermal conductance.

There are few works on transient modeling of thermal contacts, for example, [1-4]. In [5], for a one-dimensional model, it was shown that in the case of heating with short impulses, even a small thermal resistance has a significant effect on the temperature field. The present study aims at determining the nature of thermal contact conductance and estimating its temporal deviation from the steady-state value. This is based on a model problem of gyro unit–platform assembly. We will consider a calculation of the temperature field for gyro unit–platform assembly as a typical member of a platform inertial navigation system which significantly influences its temperature state [6]. In fact, thermal contact conductance varies at different points of the contact and to solve the problem we calculate the dependence of thermal contact conductance on contact pressure with our column micromodel of rough surfaces contact [7]. Then, this dependence is transferred to the finite element model of the gyro unit–platform assembly.

2. Description of gyro unit–platform model and formulation
In the right-handed Cartesian reference system, let us consider the hypothetical construction of a gyro unit attached to a platform (see Figure 2).

The model of the gyro unit is a solid cylinder with a flange, made of AISI 1020 steel. Inside the gyro unit we assume the presence of a thermostatic system maintaining on a constant level the temperature of some internal part of the device. At the same time, the temperature of the device body is not constant and is determined, among other things, by interaction with the platform. The model does not consider the internal parts and the thermostatic system as separate bodies, but it takes into account that this system generates heat with a power of 20 W, corresponding to a specific heat generation rate $q = 94832 \text{ W/m}^3$ for the given volume of the gyro unit. Heat transfer by radiation is neglected. The gyro unit is fixed from the flange onto the square platform of 1050 UNS A91050 Aluminum with four M3 bolts made of AISI 5140 steel. Half-length of the platform side $L_1 = 0.06 \text{ m}$. Distance from the bottom surface of the gyro unit to the bottom surface of the platform $L_2 = 0.035 \text{ m}$. The behavior of the bolt material is considered linearly elastic. The clamp force of each bolt $F$ is 2000 N. The joints of the parts
are in a vacuum. Isotropic dry friction according to the Amontons-Coulomb law with a friction coefficient $\mu = 0.5$, constant in the process of deformation, is taken into account in the joints. Initially, the contact surfaces of the macromodel are ideally flat. The nominal contact area of the gyro unit–platform is $1.103 \cdot 10^{-3}$ m$^2$. The model material properties are presented in Table 1.

The gyro unit–platform assembly model is constrained at the four corners of the lower platform plane as follows. One corner is constrained from displacement along all three axes $x$, $y$, $z$. The corner adjacent to it is constrained along axis $z$ and along the axis orthogonal to the connection line of the first and second corners. The third and fourth corners are constrained only along axis $z$. Thus, these constraints do not oppose thermal expansion, i.e., do not cause additional thermal stresses.

### Table 1. Material properties of the model.

| Part                  | Gyro unit | Bolts          | Platform        |
|-----------------------|-----------|----------------|-----------------|
| Material grade        | AISI 1020 steel | AISI 5140 steel  | 1050 UNS A91050 aluminum |
| Modulus of elasticity $E$, GPa | 212       | 212            | 71              |
| Poisson ratio $\nu$   | 0.36      | 0.3            | 0.32            |
| Yield strength, MPa   | 280       | -              | 55.7            |
| Linear coefficient of thermal expansion $\alpha$, 1/°C | 11.1$\cdot 10^{-6}$ | 12$\cdot 10^{-6}$ | 23.5$\cdot 10^{-6}$ |
| Thermal conductivity $k$, W/(m·°C) | 86        | 41             | 210             |
| Specific heat capacity $c_p$, J/(kg·°C) | 461       | 466            | 858             |
| Mass density $\rho$, kg/m$^3$ | 7850      | 7810           | 2710            |

In this model, we assume the absence of axial and bending external forces that may affect the area of actual contact [8].

On the right wall of the platform, heat is removed with an intensity of $h = 500$ W/(m$^2$·°C) and coolant temperature $T_{coolant} = 20$ °C. Thermal expansion was taken into account when calculating the assembly model. Reference temperature is $T_0 = 20$ °C. The coupled problem of heat conductance and deformation in a static setting was solved. All loads were applied simultaneously in a single load step.

Let us move on to the index designations of axes of the Cartesian reference system $x_i$, $i = 1,2,3$. The following mathematical model corresponds to the problem, including equilibrium equations (1), the generalized Hooke’s law (2), the flow rule (3), thermal strain relation (4), strain-displacement relations (5), von Mises yield condition (6), ratio for calculation of contact pressure of augmented Lagrangian method (7), Amontons-Coulomb friction law (8) on the contact surface, structural boundary conditions (9)-(12), heat equation (13), initial condition (14), and thermal boundary condition (15):

$$
\sigma_{i,j} = 0; \\
\varepsilon_{ij} = \frac{1+\nu}{E}(\sigma_{ij} - \nu \delta_{ij}\sigma_{kk}); \\
d\varepsilon_j^p = s_{ij}d\lambda; \\
d\varepsilon_{ij}^T = \alpha(T - T_0); \\
\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}); \\
(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\Phi(\varepsilon^p)^2; \\
p(x_i) = K\delta + \lambda_c, x_i \in S_c;
$$
where \( \sigma_{ij} \) and \( \varepsilon_{ij} \) are the Cartesian components of tensors of stress and strain, \( u_i \) are the components of displacements vector, \( \delta_{ij} \) is the Kronecker delta, \( s_{ij} \) are the components of stress deviator tensor, \( T \) is the temperature, \( \sigma_1, \sigma_2, \sigma_3 \) are the principal stresses, \( \lambda, \lambda_c \) are Lagrange multipliers, \( \Phi(\bar{e}^p) \) is the function of the material’s stress-strain curve, \( p \) is the contact pressure, \( K \) is the contact stiffness, \( \delta \) is the contact gap size, \( \tau_c \) is the tangential stress on the contact surface, \( S_c \) is the surface of contacts, \( n \) is a bolt index, \( S_n^D \) is a cross section of bolt \( n \), \( A_n \) is an area of \( S_n^D \), \( \Delta \) is the Laplace operator, \( S_{conv} \) is the cooled platform surface.

The problem is solved using ANSYS finite element software. For the simulation of bolts, pretension type of analysis and PRETS179 finite elements are used. The finite element mesh of the assembly model is shown in Figure 3.

\[
\tau_c \leq \mu p(x_i), \; x_i \in S_c; \quad (8) \\
\sigma_{33}^n(x_3) = \frac{F}{A_n}, \; x_3 \in S_n^D, n = 1 \ldots 4; \quad (9) \\
u_i \big|_{x_i = (l_1, -l_1, l_2)} = 0; \quad (10) \\
u_1 \big|_{x_i = (-l_1, -l_1, l_2)} = 0, u_2 \big|_{x_i = (-l_1, -l_1, l_2)} = 0; \quad (11) \\
u_3 \big|_{x_i = (-l_1, l_1, l_2)} = 0, u_3 \big|_{x_i = (l_1, l_1, l_2)} = 0; \quad (12) \\
c_p \rho \frac{\partial T}{\partial t} - k \Delta T - q = 0; \quad (13) \\
T = T_0, t = 0; \quad (14) \\
-k \frac{\partial T}{\partial x_1} = h(T - T_{coolant}), \; x_1 \in S_{conv} \quad (15)
\]

Figure 3. Finite element mesh of the assembly model.

To determine the contact pressure and gaps for all contact areas, the Standard contact type is selected in the ANSYS options. Augmented Lagrange method is used as a contact algorithm with Gauss point contact detection method.

On the contact finite elements of the macromodel thermal contact conductance is specified as the TCC parameter of ANSYS. In the assembly, it is possible to define the contact of the gyro unit – platform, which is the most influential in the heat transfer, and the contacts of the gyro unit – bolts and the platform – bolts. For two latter contacts the TCC parameter is estimated to be 100,000 W/(m²·°C).

Since the bolts form a field of contact pressures markedly different from uniform, the thermal contact conductance is specified tabularly as a function of pressure TCC(\( p \)) where \( p \) is the contact pressure on a specific finite element. This dependence is obtained from the calculation of the column micromodel of contact rough bodies with dimensions 90x90x1125 μm described in [7], taking into account the indentation size effect (ISE).

The calculations were carried out within the approach of small displacements, since, according to the results of preliminary calculations, the inclusion of large displacements led to an insignificant change in the result.
The temperature field of the macromodel was determined, and then, the averaged over the nominal area thermal contact conductance of the gyro unit – platform contact region was calculated by the relation

\[ \bar{\alpha}_c = \frac{\bar{q}}{\bar{T}_2 - \bar{T}_1} \]

where \( \bar{q} \) is the average heat flux density over the area of finite elements of the lower nominal surface, \( \bar{T}_1 \), \( \bar{T}_2 \) are the average temperatures over the area of finite elements of the nominal lower and upper contact surfaces, respectively.

The model takes into account the effect of thermal expansion on the real contact area. Because of the change in shape of the cylindrical body of the gyro unit, tangency takes place in the form of a narrow ring along the outer edge of the nominal contact area. Also, areas near the bolts are in direct contact.

The selected interval of the calculations ranges from 0 to 7000 s which is of interest from the engineering point of view for similar constructions of platform inertial navigation systems.

3. Numerical simulation and results

The calculation results have shown that the maximum stresses in the structure do not exceed the yield strength. The thermoelastic effect, where the redistribution of stresses can lead to a temperature change, is neglected, since even at the pressure of 1-2 GPa it can result in a short-term temperature alteration only by 0.1-1% [9]. Therefore, the coupled thermomechanical problem has been solved without taking thermoelastic damping into account.

When solving a transient problem, the Newmark model and the High Speed time integration mode are used. Stepped loading is used and in order to avoid solution oscillations, a sufficiently small time step was taken in accordance with Table 2.

| Time period, s | Time step, s |
|---------------|-------------|
| 0.001-0.1     | 0.001       |
| 0.1-0.2       | 0.002       |
| 0.2-20        | 0.01        |
| 20-320        | 1           |
| 320-700       | 2           |
| 700-3000      | 10          |
| 3000-50000    | 100         |

With small time steps, it is especially difficult to calculate the first step. The solution requires a large number of intermediate iterations (several dozens).

The results have been compared with the steady-state solution, which we obtained earlier in [6] for the same formulation. The calculated thermal contact conductance of the gyro unit–platform connection averaged by the nominal area was \( \alpha_c = 20739 \text{ W} / (\text{m}^2 \cdot ^\circ \text{C}) \). The maximum temperature of the gyro unit was 61.53 \(^\circ\text{C}\).

Before the heating starts, the bolts are tightened and the parts are pressed together. At this moment, the thermal contact conductance equals infinity, since the structure has uniform temperature field and the temperature jump of the contact equals 0. During the first time step, the instantaneous value of thermal contact conductance, which is usually not far from the steady-state one, is determined. It grows over time, reaches its maximum and decreases below the steady-state value (see Figures 4, 5). Then it grows reaching the second maximum and decreases to the value which exceeds the steady-state one by about 5% (see Figure 6). The first maximum, which becomes apparent at a small time step, is explained by the proximity to the singularity that results in temperatures less than \( T_0 \) in the numerical solution. The appearance of the second maximum during heating is characteristic of flat–flat contacts.
[10] and is related to thermal expansion of parts. The final value obtained in the solution differs from the steady-state one due to the errors of the finite element method.

![Graph](image1)

**Figure 4.** The change of the thermal contact conductance of the gyro unit–platform assembly (up to 1 s).

![Graph](image2)

**Figure 5.** The change of thermal contact conductance of gyro unit–platform assembly (up to 300 s).

![Graph](image3)

**Figure 6.** The change of thermal contact conductance of gyro unit–platform assembly (up to 7000 s).

The fluctuations in thermal contact conductance on the interval of 20–7000 s give a deviation from the steady-state value from −6% to +11%. This deviation leads to a change in the temperature field of this assembly model by less than 0.1 °C, which can be neglected in engineering practice. Nevertheless, it may be noticeably larger in other contacts and, moreover, this deviation is significant from theoretical...
point of view as it shows a considerable contribution of transience to the thermal contact model. It should be noted that the deviation could be substantially greater with smaller bolt clamping force. Figures 7-9 show the variation of heat flux, averaged temperatures in the contact and the temperature jump versus time. The form of these variations depends entirely on the size and configuration of the parts in a contact, the thermophysical and mechanical properties of materials, and the conditions of the contact. Apparently, the variations change monotonously and even in such conditions there is a significant change in thermal contact conductance. The thermal contact conductance of this contact practically reaches its steady-state value within the taken period of 7000 seconds.

![Figure 7](image7.png)

**Figure 7.** The change of heat flux versus time.

![Figure 8](image8.png)

**Figure 8.** Average temperatures of the surfaces in contact versus time.

![Figure 9](image9.png)

**Figure 9.** Temperature jump versus time.

4. **Conclusion**

It has been determined that the thermal contact conductance in the process of even heating of a structure varies considerably, both exceeding its steady-state value and going below it. In engineering practice, the transient behavior of responsible contacts can be analyzed by means of commercial finite
element software provided that we have the dependence of thermal contact conductance on contact pressure. The widespread approach of calculation using only one constant contact-specific value of thermal contact conductance is insufficient in this case. The obtained deviation of 11% is of great value for the developers of thermal contact models as it places consideration of transience among significant processes in modeling.

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