MATERIAL SURFACE THERMAL PROPERTY IDENTIFICATION USING HEAT FLUX TACTILE SENSOR

Wu Jianfeng, Mao Zhipeng, Li Jianqing, Zhou Lianjie, Cai Feng

(School of Instrument Science and Engineering, Southeast University, Nanjing, 210096, P. R. China)

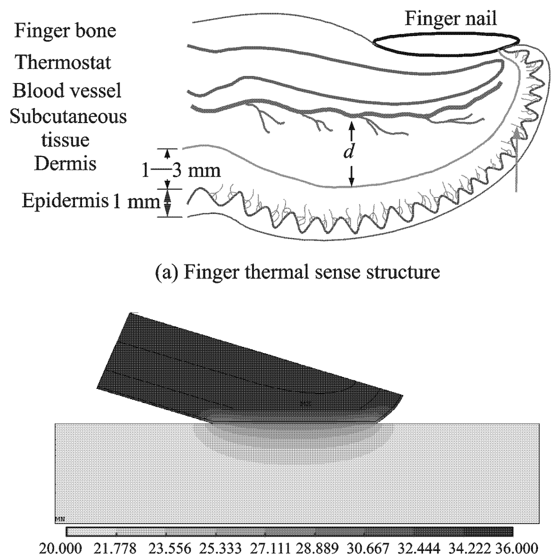
Abstract: Based on the mechanism of temperature tactile sensing of human finger, a heat flux tactile sensor composed of a thermostat module and a heat flux sensor is designed to identify material thermal properties. The thermostat module maintains the sensor temperature invariable, and the heat flux sensor (Peltier device) detects the heat flux temperature difference between the thermostat module and the object surface. Two different modes of the heat flux tactile sensor are proposed, and they are simulated and experimented for different material objects. The results indicate that the heat flux tactile sensor can effectively identify different thermal properties.

Key words: heat flux tactile sensor; heat flux; material identification; Peltier device; ANSYS finite element method (FEM) simulation

CLC number: TP391 **Document code:** A **Article ID:** 1005-1120(2012)01-0084-06

INTRODUCTION

Previous researches show that human finger skin is sensitive to temperature change[1-2]. The finger structure is shown in Fig. 1 (a), its sensitivity is mainly due to lots of thermo receptors within the skin of finger. When the finger touches an object, its surface temperature rapidly changes to the object surface temperature, so a changing temperature field is formed in the finger in a short time, as shown in Fig. 1(b). When the various temperature fields act on the thermo receptors, different sensations are formed. In them, cold receptors (Krause's end-bulbs) receive the cold sensation, and hot ones (Ruffini's corpuscles) receive the hot sensation[3-4]. As the distribution density of Krause's end-bulbs is larger than that of Ruffini's corpuscles, human finger is more sensitive to the cold sensation than the hot sensation. The change process of temperature field in finger is related to the initial temperature difference between the object and the finger, and the material and surface morphology of objects.



(b) Finger thermal sense simulation model

Fig. 1 Finger thermal sense structure and simulation model

Temperature tactile sensor is used to evaluate the human sensory nerve fibers[3-4], and to identify the surface thermal properties[5-9]. Combined with other tactile sensors, such as pressure

Foundation items: Supported by the National High Technology Research and Development Program of China ("863" Program) (2009AA01Z314, 2009AA01Z311); the Jiangsu Province Natural Science Foundation (BK2009272); the Jiangsu Province "333" Program.

Received date: 2010-12-03; **revision received date:** 2011-06-10

E-mail: wjf@seu.edu.cn

tactile sensor[2], the sensor can constitute a multi-function tactile sensor similar to human skin.

In this paper, a heat flux tactile sensor is designed based on heat flux sensor, and it is used to identify different thermal properties of the object. Experimental results show that the heat flux tactile sensor has good performance.

1 HEAT FLUX TACTILE SENSOR

The structure of heat flux tactile sensor is shown in Fig. 2. It is composed of a thermostat module, a heat flux sensor and its measurement and control unit. In the sensor, the thermostat module integrates temperature sensing unit and heating unit. The temperature control unit maintains thermostat module temperature invariable, and heat flux sensor detects heat flux temperature difference between the sensor and the measured object when they contact. Heat flux voltage is detected by the voltage measurement unit. Heat flux sensor causes a thermal resistance between the thermostat module and the measured object, and the resistance value depends on thickness and material of the the heat flux sensor. For objects with different materials, their thermal conductivities, densities and specific heat capacities are also different. So voltages output curves of heat flux sensor in the contact process are different. Heat

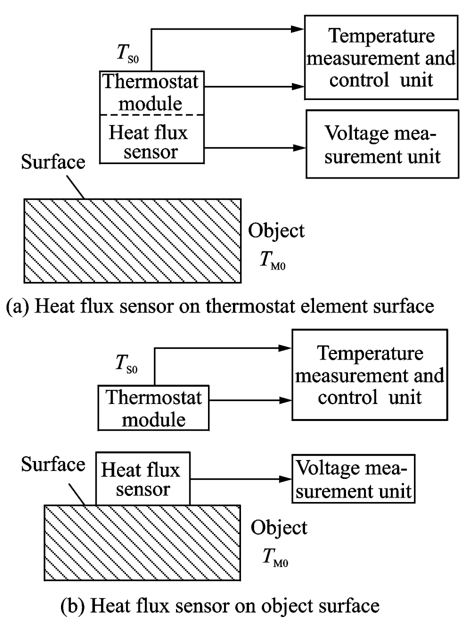


Fig. 2 Heat flux tactile sensor on different surfaces

flux sensor can be affixed on the thermostat module (T mode) or on the measured object (O mode). For two various affixing methods, heat flux sensor responses are different.

In the heat flux tactile sensor, a Peltier device is adopted as heat flux sensor. Its voltage output is related to temperature difference between its top and bottom surfaces. From the Thomson effect, the temperature difference electromotive force of the Peltier device mainly comes from its volume electromotive force, and its Seebeck coefficient can reach 1 000 μV/K[10]. There fore, a small temperature difference between top and bottom surfaces of the Peltier device can produce a large voltage output.

2 IDENTIFICATION MECHANISM USING HEAT FLUX TACTILE

According to the classical heat conduction theory[11], when heat flux tactile sensor contacts with measured objects and the surface contact thermal resistance is ignored, the surface has continuous boundary conditions and same heat flux density. From the contact moment, heat flux occurs between the heat flux tactile sensor and the measured object for temperature difference between them.

Different from T mode or O mode, the heat flux sensor has different voltage outputs for the different heat fluxes.

In the O mode, the initial temperature of heat flux sensor is the same with that of object. When the thermostat module contacts with the heat flux sensor, the top surface temperature of heat flux sensor reaches the temperature of the thermostat in a short time, and a changing temperature field is rapidly formed in the heat flux sensor. Assuming T_{S0}, T_{M0} are the initial temperature of the thermostat and the measured object, temperature difference between the top and bottom surfaces is

$$T_d(t) = (T_{S0} - T_{M0})\left\{1 - \left[(1-\gamma)\mathrm{erfc}\left(\frac{-L}{2\sqrt{\alpha_S t}}\right) + \gamma(1+\gamma)\sum_{n=0}^{\infty}(-1)^n\gamma^n \mathrm{erfc}\frac{(2n+1)L}{2\sqrt{\alpha_S t}}\right]\right\} \quad (1)$$

where $\gamma = (\beta_S - \beta_M)/(\beta_S + \beta_M)$, L is the thickness of heat flux sensor, $\beta_M = (\lambda_M \rho_M c_M)^{1/2}$ and $\beta_S = (\lambda_s \rho_s c_s)^{1/2}$ are the thermal absorption coefficients of object and sensor, $\alpha = \lambda/(\rho c)$ is the thermal diffusivity, λ, ρ, c are the thermal conductivity, density, and specific heat capacity, and $\mathrm{erfc}(u) = 1 - \frac{2}{\pi}\int_0^u e^{-x^2}dx$.

At the initial of O mode, the heat flux between the heat flux sensor and the thermostat module is maximal, while the heat flux from sensor to objects is zero.

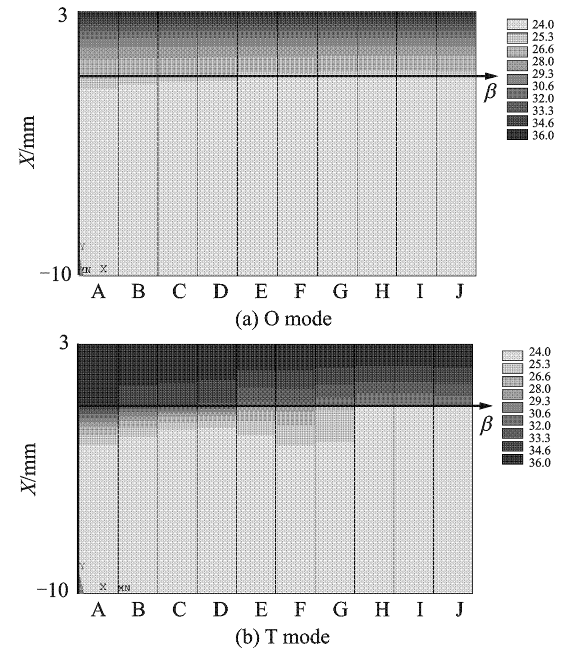
In the T mode, the initial temperature of heat flux sensor is the same with that of the thermostat. When the sensor contacts with the object, the bottom surface temperature of the heat flux sensor reaches the temperature of the object in a short time. And a changing temperature field is rapidly formed in the heat flux sensor. The temperature difference between the top and bottom surfaces is

$$T_d(t) = (T_{S0} - T_{M0})\frac{1-\gamma}{2}\sum_{n=0}^{\infty}(-1)^n\gamma^n \cdot \left\{\mathrm{erfc}\left[\frac{nL}{\sqrt{\alpha_S t}}\right] - \mathrm{erfc}\left[\frac{(n+1)L}{\sqrt{\alpha_S t}}\right]\right\} \quad (2)$$

At the initial state of this mode, the heat flux between the heat flux sensor and the thermostat is zero, while the heat flux from sensor to object is maximal.

When the tactile sensor contacts with objects with different thermal properties, with the heat-absorbing coefficient β decreasing, the main temperature distribution in the heat flux sensor is transferred to the measured object in two modes. Their different distributions are shown in Fig. 3 (at 4 s).

As shown in Fig. 3, the heat flux sensor has different output curves when contacting with different objects, so the various thermal properties can be effectively identified.



A—Cotton, B—Wood, C—Plastic, D—Rubber, E—Glass, F—Ceramic, G—Marble, H—Stainless steel, I—Fe, J—Al

Fig. 3 Heat flux change between sensor and objects

3 ANSYS FINITE ELEMENT METHOD SIMULATION

3.1 ANSYS FEM Model

The thermal tactical perception is simulated in thermal model of ANSYS. When the sensor contacts with the object, thermal conduction mainly occurs in the direction vertical to contact surface. In simulating, the thermostat element can be idealized as constant temperature surface. Within a limited time, the temperature perturbation does not penetrate through the measured object. The outside part of the penetration depth maintains the original temperature. Therefore the size of the measured object is small[11]. As shown in Fig. 4, ANSYS FEM model of the thermostat module is a thin plate. Its length and width are both 20 mm, and its thickness is 1.74 mm.

The Peltier device has ANSYS FEM model with the ceramics surface and the semiconductor interior. The thickness of the model is 3 mm, and its length and width are both 9 mm. The ANSYS FEM model of measured object is a thick plate. Its length and width are both 40 mm, and its thickness is 10 mm. Because of symmetry, only

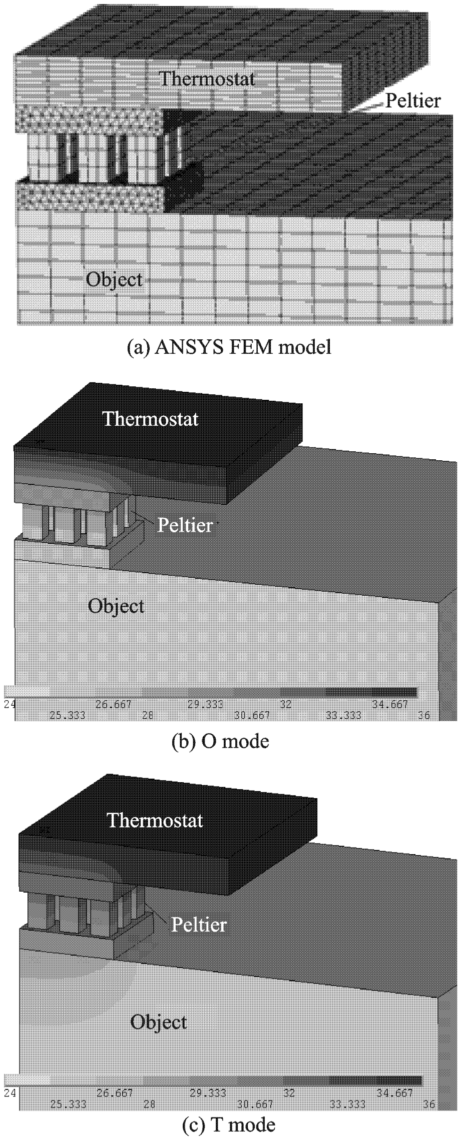


Fig. 4 ANSYS FEM model

1/4 model is displayed. SOLID70 hexahedral units are used for dividing thermostat board, the semiconductor interior of Peltier device and objects. SOLID70 tetrahedral units are used for dividing the ceramics surface of Peltier device. Set the temperature of the thermostat module to 36℃. The initial temperature of sensor is set according to the contact mode. In the O mode, it is set to 24 ℃. In the T mode, it is set to 36 ℃, the initial temperature of measured object is 24℃.

3.2 Thermal tactile sensing simulation for different material objects

Different material objects with smooth surface are simulated, and the results are shown in Fig. 5.

Simulation results in the O mode are shown in Fig. 5(a). When the thermostat contacts with the heat flux sensor, at the initial stage (less than 2 s), for all kinds of materials, temperature difference between top and bottom surfaces of the heat flux sensor increases at a similar rate, and their temperature difference curves are so similar that they are difficult to distinguish. After that, the increase rates of temperature difference of various materials begin to decrease. For the objects with smaller β, their temperature difference tends to maximum value, and for the objects with larger β, their temperature difference increases slowly. Eventually, temperature difference curves of objects with larger β directly tend to their final temperature difference, and those with smaller β begin to decline and then tend to their final temperature difference. Objects with smaller β have apparent peaks, objects with similar β to flux sensor have unapparent peaks, while objects with larger β have no peak.

Simulation results in the T mode are shown in Fig. 5 (b), when the thermostat contacts with objects through heat flux sensor, at the initial stage, temperature difference between top and bottom surfaces of the heat flux sensor increases at a quite different rate for the materials with various thermal properties. After a short time (less than 2 s), temperature difference curves of different materials can be distinguished easily. Then the increase rates of temperature difference of various materials begin to decrease, and all the curves have peaks. For objects with larger β, their peaks are apparent. For the objects with smaller β, their peaks are unapparent comparatively. Eventually, all curves tend to a flat final temperature difference. Other simulations show that the time when peak value occurs have no apparent definite relationship with β, so β cannot be judged by the time when peak value occurs.

The simulations of two modes both show that, the final temperature difference of various objects is related to β. The larger β is, the larger the final temperature difference is. The objects cannot be identified in a short time in the O

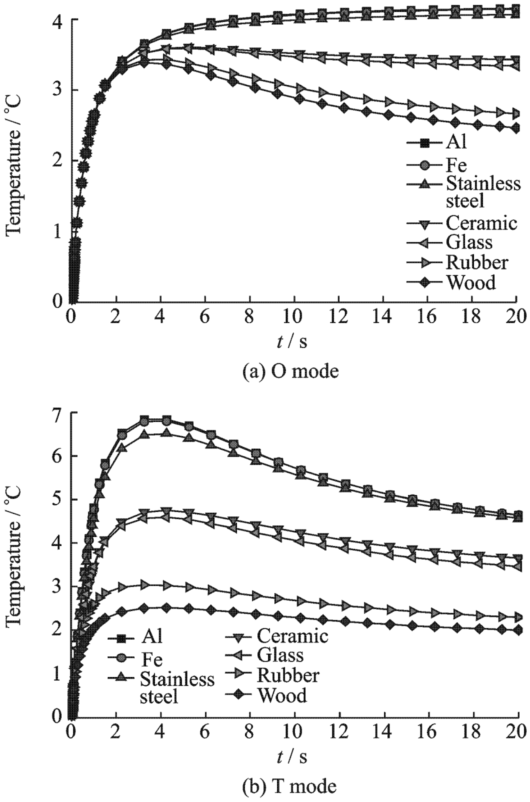


Fig. 5 Simulation results of different materials

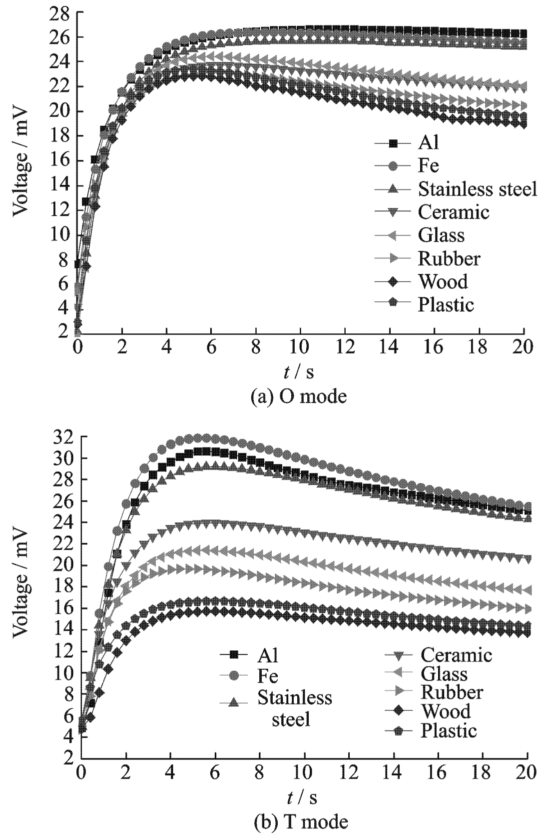


Fig. 6 Experimental results of different materials

mode, but the objects with smaller β can be more easily distinguished by the peak of temperature difference. In the T mode, objects with various β can be identified by different temperature difference curves in a short time, but objects with smaller β are difficult to identify for their small peaks of temperature difference curves.

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Heat flux tactile sensor is applied to tactile conduct experiment for the different material objects. The temperature of thermostat module is 36 ℃, and ambient temperature is 24 ℃.

4.1 Experimental results

Different material objects are tested using heat flux tactile sensor in O mode and T mode, the results are shown in Fig. 6.

4.2 Discussions

Experimental results in two modes show that the final temperature difference of various objects is related to β. The larger β is, the larger its final temperature difference is.

The results also show that, in the O mode, the temperature difference curves of various objects are similar and difficult to be distinguished in a short time. And apparent voltage peaks occur for the objects with smaller β. But for the objects with larger β, their peaks are unobvious and even there is no peak at all. In the T mode, temperature difference curves of various objects are apparently different. Therefore objects can be identified easily and rapidly. In this mode, the voltage peaks of temperature difference curves are more apparent for the object with larger β, so the T mode is more suitable for identifying objects.

The change rate of temperature difference in the experiment is slower than that of simulation, and it needs longer time to tend to the final temperature difference. The possible reasons are that in simulation the surfaces of sensor and measured objects are completely smooth, while a certain surface roughness and corrugation cannot be avoid in the contact with real objects. This causes a flowing air gap between the sensor and the measured objects. The gap forms a certain thermal resistance, which makes the change rate of temperature difference slow down.

5 CONCLUSION

In this paper, the mechanism of temperature tactile sensing of human finger is studied. Then, a heat flux tactile sensor is designed to identify material thermal properties, and its mechanism is analyzed. The results indicate that FEM simulation and experimental results have a good accordance, and the sensor can effectively identify objects with different thermal properties. Under a good contact condition, the curves of different material objects separate early and the biggest temperature difference of various materials occurs at about 4 s.

References:

[1] Yamamoto A, Cros B, Hashimoto H, et al. Control of thermal tactile display based on prediction of contact temperature[C]//Proceedings of the 2004 IEEE International Conference on Robotics & Automation. New Orleans: IEEE, 2004: 1536-1541.

[2] Takamuku S, Iwase T, Hosoda K. Robust material discrimination by a soft anthropomorphic finger with tactile and thermal sense[C]//2008 IEEE/RSJ International Conference on Intelligent Robots and Systems. Nice, France: Acropolis Convention Center, 2008: 3977-3982.

[3] Selim M M, Wendelschafer-Crabb G, Hodges J S. Variation in quantitative sensory testing and epidermal nerve fiber density in repeated measurements [J]. PAIN, 2010, 151(3): 575-581.

[4] Rolke R, Magerl W, Campbell K A. Quantitative sensory testing: A comprehensive protocol for clinical trials [J]. European Journal of Pain, 2006, 10(1): 77-88.

[5] Russell R A. Thermal sensor array to provide tactile feedback for robots [J]. International Journal of Robotics Research, 1985, 4(3): 35-39.

[6] Siegel D, Inaki G, Hollerach J M. An integrated tactile and thermal sensor[C]//Proceedings of IEEE International Conference on Robotics and Automation. San Francisco, CA, USA: IEEE, 1986: 1286-1291.

[7] Wouter M, Tiest B, Kappers A M L. Discrimination of thermal diffusivity [C]//Third Joint Euro haptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Salt Lake City, UT, USA: IEEE, 2009: 635-639.

[8] Morimitsu H, Katsura S. Heat inflow control of peltier device based on heat inflow observer [C]// SICE Annual Conference. Taipei, Taiwan, China: SICE, 2010: 996-1001.

[9] Jones L A, Ho Hsin-Ni. Warm or cool, large or small? The challenge of thermal displays [J]. IEEE Transactions on Haptic, 2008, 1(1): 53-70.

[10] Xu Desheng. Semiconductor refrigeration and application technology [M]. Shanghai: Shanghai Jiaotong University Press, 1991. (in Chinese)

[11] Zhao Zhengnan. Heat transfer [M]. Beijing: Higher Education Press, 2008. (in Chinese)

基于热流触觉传感器的物体表面热属性识别

吴剑锋　毛志鹏　李建清　周连杰　蔡　凤

(东南大学仪器与科学工程学院,南京,210096,中国)

摘要:基于人手热觉感知机理,设计了一种热流触觉传感器,该传感器由恒温元件和热流传感器构成。恒温元件保持热流敏感元件热端恒温,热流传感器检测传感器与被测物体表面间的热流温差,热流传感器采用玻尔贴器件。设计了两种不同方式的热流触觉传感方式。分析了采用热流触觉识别材料热属性的方法,具有温度差异的传感器与物体相接触,在传感器和物体间形成热流,不同材料物体热流不同,并对不同材料的物体进行了热流触觉仿真和试验。结果表明,所研制的热流触觉传感器能较好地识别不同热属性的物体。

关键词:热流触觉传感器;热流;材料识别;玻尔贴器件;ANSYS 有限元仿真

中图分类号:TP391

(Executive editor: Zhang Huangqun)

基金项目:国家高技术研究发展计划(“八六三”计划)(2009AA01Z314,2009AA01Z311)资助项目;江苏省自然科学基金(BK2009272)资助项目;江苏省“333”计划资助项目。