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Vibration of microscale beam induced by laser pulse

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Abstract

In the case of ultra-short-pulsed laser heating, two effects become domineering. One is the non-Fourier effect in heat conduction, and the other is the coupling effect between temperature and strain rate. In the present study, a generalized solution for the coupled thermoelastic vibration of a microscale beam resonator induced by pulsed laser heating is developed. The solution takes into account the above two effects. The combined finite sinusoidal Fourier and Laplace transformation method is used to determine the lateral vibration of the beam. The effects of laser pulse energy absorption depth and reference temperature have been studied.

1. Introduction

Excitation of thermoelastic waves by a pulsed laser in solid is of great interest to many researchers due to extensive application of pulsed laser technologies in material processing and non-destructive detecting and characterization. When a solid is illuminated with a laser pulse, absorption of the laser pulse results in a localized temperature increase, which in turn causes thermal expansion and generates a thermoelastic wave in the solid [1,2].

The so-called ultra-short lasers are those with pulse duration ranging from nanoseconds to femtoseconds in general [3,4]. In the case of ultra-short-pulsed laser heating, two effects become domineering. One is the non-Fourier effect in heat conduction, which is a modification of the Fourier heat conduction theory. In most engineering applications of conventional laser heating using a relatively low energy flux and long pulse duration, the conduction heat transfer has been successfully modeled by the Fourier theory. Rapid developments on laser techniques, such as the high-intensity and ultra-short duration laser beam, however, have introduced situations where very large thermal gradients or an ultra-high heating speed may exist at the boundaries. In such cases, as pointed out by many investigators, the classical Fourier model, which leads to an infinite propagation speed of the thermal signal, is no longer valid [5–6]. The non-Fourier effect of heat conduction takes into account the effect of mean free time (thermal relaxation time) in the energy carrier's collision process, which can eliminate this contradiction. The other is the coupling between temperature and

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strain rate, which causes transfer of mechanical energy associated with the stress wave to thermal energy of the material. And this process is irreversible.

To-date, the classical Fourier heat conduction theory is widely employed, whereas, the non-Fourier heat conduction theory is seldom used, for the study of microscale beams. At present, there are two different theories of the generalized thermoelasticity: the first was developed by Lord and Shulman (L–S) [7], and the second by Green and Lindsay (G–L) [8]. The former theory is based on the modified Fourier's law of heat conduction, and implements one relaxation time. Whereas, the latter theory was established by modifying both the energy equation and the Duhamel–Meumann relation and implementing two relaxation times.

The classical Fourier heat conduction equation is a parabolic equation, whereas, the non-Fourier heat conduction equation is a hyperbolic equation, which is much more complicated to solve. By employing the L–S model, Hany et al. [9] obtained the distributions of thermal stresses and temperature for a generalized thermoelastic problem in which an infinite elastic space was subjected to the influence of a continuous line source of heat. The solution of the problem was obtained by applying the Hankel and Laplace integral transforms successively. Mohamed et al. [10] adopted the state space approach to solve one-dimensional problems in generalized thermoelasticity using one relaxation time. The said technique was applied to a thermal shock half-space problem and a layered medium problem. Tang [11] considered transient heat conduction in a finite medium exposed to a pulsed surface heating using the generalized macroscopic conduction model. The analytical solution was obtained using the Green's function method and finite integral transformation technique.

Micro- and nano-mechanical resonators have attracted considerable attention recently due to their many important technological applications. Accurate analysis of various effects on the characteristics of resonators, such as resonant frequencies and quality factors, is crucial for designing high-performance components. Many authors have studied the vibration and heat transfer process of beams. Kidawa [12] has studied the problem of transverse vibrations of a beam induced by a mobile heat source. The analytical solution to the problem was obtained using the Green's functions method. However, Kidawa did not consider the thermoelastic coupling effect. Boley [13] analyzed the vibrations of a simply supported rectangular beam subjected to a suddenly applied heat input distributed along its span. Manolis and Beskos [14] examined the thermally induced vibration of structures consisting of beams, exposed to rapid surface heating. They have also studied the effects of damping and axial loads on the structural response. Al-Huniti et al. [15] investigated the thermally induced displacements and stresses of a rod using the Laplace transformation technique.

The above-mentioned papers have hardly studied the vibration of microscale beam resonators induced by ultra-short-pulsed laser by considering the thermoelastic coupling term. In the present study, a generalized solution for the coupled thermoelastic vibration of a microscale beam resonator induced by pulsed laser heating is developed. The finite sinusoidal Fourier transformation combined with Laplace transformation is used to obtain the lateral vibration of the beam. Moreover, the effects of different laser pulse durations and beam thicknesses are also studied.

2. Problem formulation

Since beams with rectangular cross-sections are easy to fabricate, such cross-sections are commonly adopted in the design of MEMS resonators. Consider small flexural deflections of a thin elastic beam of length $L(0 \leqslant x \leqslant L)$, width $b(-b/2 \leqslant y \leqslant b/2)$ and thickness $h(-h/2 \leqslant z \leqslant h/2)$, for which the x, y and z axes are defined along the longitudinal, width and thickness directions of the beam, respectively. In equilibrium, the beam is unstrained, unstressed, and at temperature T_0 everywhere.

In the present study, the usual Euler–Bernoulli assumption [16] is adopted, i.e., any plane cross-section, initially perpendicular to the axis of the beam, remains plane and perpendicular to the neutral surface during bending. Thus, the displacements are given by

$$u = -z\frac{\mathrm{d}w}{\mathrm{d}x}, \quad v = 0, \quad w(x, y, z, t) = w(x, t). \tag{1}$$

The differential equation of thermally induced lateral vibration of the beam may be expressed in the form:

$$EI\frac{\partial^4 w}{\partial x^4}+\rho A\frac{\partial^2 w}{\partial t^2}+\frac{\partial^2 M_T}{\partial x^2}=0, \tag{2}$$

where EI, ρ, w, x, t and M_T denote the bending rigidity, density, lateral beam deflection, distance along the length of the beam, time and thermal moment, respectively; $\beta = E\alpha/(1/2v)$, in which α is the coefficient of thermal expansion, E is Young's modulus of the material of the beam, $\theta = T - T_0$ is the temperature increment of the resonator, $T(x,z,t)$ is the temperature distribution in the beam and T_0 is the reference temperature:

$$M_T = b\beta\int_{-h/2}^{h/2}\theta(x,z,t)z\,\mathrm{d}z. \tag{3}$$

Assume that $K = M_T/b\beta h^2 = \int_{-h/2}^{h/2}\theta z\,\mathrm{d}z/h^2$, thus, Eq. (2) can be expressed as

$$\frac{Eh^2}{12}\frac{\partial^4 w}{\partial x^4}+\rho\frac{\partial^2 w}{\partial t^2}+\beta h\frac{\partial^2 K}{\partial x^2}=0. \tag{4}$$

The initial temperature distribution in the beam is $T(x,z,0) = T_0$, i.e., $\theta(x,z,0) = 0$. From $t = 0$, the upper surface ($z = h/2$) of the beam is heated uniformly by a laser pulse with non-Gaussian form temporal profile, as shown in Fig. 1, as follows:

$$I(t)=\frac{I_0 t}{t_p^2}\exp\left(-\frac{t}{t_p}\right), \tag{5}$$

where t_p is a characteristic time of the laser-pulse, I_0 is the laser intensity which is defined as the total energy carried by a laser pulse per unit cross-section of the laser beam.

In accordance with Ref. [11], the conduction heat transfer in the beam can be modeled as a one-dimensional problem with an energy source $Q(z,t)$ near the surface, i.e.,

$$Q(z,t)=\frac{1-R}{\delta}\exp\left(\frac{z-h/2}{\delta}\right)I(t)=\frac{1-R}{\delta}\frac{I_0 t}{t_p^2}\exp\left(\frac{z-h/2}{\delta}-\frac{t}{t_p}\right), \tag{6}$$

where δ is the absorption depth of heating energy and R is the surface reflectivity.

The non-Fourier heat conduction equation involving the thermoelastic coupling term has the following form:

$$k\theta_{,ii}+Q(z,t)=\rho c_v\frac{\partial\theta}{\partial t}+\beta T_0\frac{\partial u_{i,i}}{\partial t}+\tau_0\rho c_v\frac{\partial^2\theta}{\partial t^2}+\tau_0\beta T_0\frac{\partial^2 u_{i,i}}{\partial t^2}, \tag{7}$$

where k, c_v and τ_0 are the thermal conductivity, specific heat at constant volume and relaxation time, respectively.

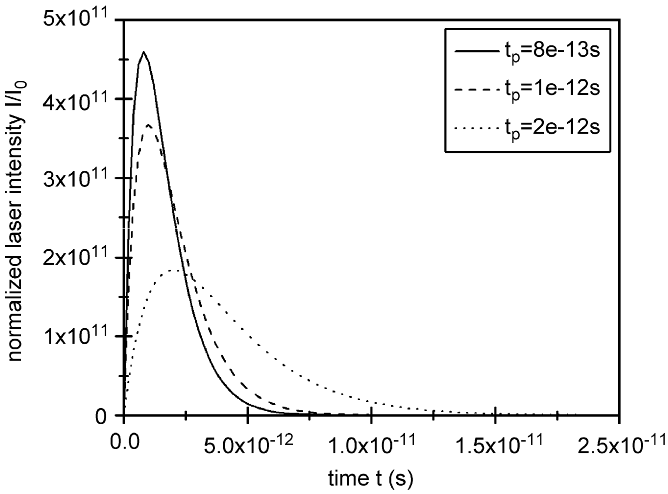

Fig. 1. The temporal profiles of the heating laser with different pulse durations.

Substituting Eqs. (1) and (6) into Eq. (7) yields,

$$k\frac{\partial^2 \theta}{\partial x^2} + k\frac{\partial^2 \theta}{\partial z^2} + \frac{1-R}{\delta}\frac{I_0 t}{t_p^2}\exp\left(\frac{z-h/2}{\delta} - \frac{t}{t_p}\right) = \rho c_v \frac{\partial \theta}{\partial t} - T_0\beta z\frac{\partial^3 w}{\partial x^2 \partial t} + \tau_0 \rho c_v \frac{\partial^2 \theta}{\partial t^2} - \tau_0 T_0 \beta z \frac{\partial^4 w}{\partial x^2 \partial t^2}. \tag{8}$$

There is no flow of heat across the upper and lower surfaces of the beam, i.e.,

$$\frac{\partial \theta}{\partial z} = 0, \quad z = \pm h/2. \tag{9}$$

Multiplying Eq. (8) by z/h^2, and integrating it with respect to z from $-h/2$ to $h/2$, yields

$$k\frac{\partial^2 K}{\partial x^2} + k\int_{-h/2}^{h/2}\frac{1}{h^2}\frac{\partial^2 \theta}{\partial z^2} z\,\mathrm{d}z - \rho c_v \frac{\partial K}{\partial t} + T_0\beta\frac{h}{12}\frac{\partial^3 w}{\partial x^2 \partial t} - \tau_0 \rho c_v \frac{\partial^2 K}{\partial t^2} + \tau_0 T_0 \beta \frac{h}{12}\frac{\partial^4 w}{\partial x^2 \partial t^2} + \frac{1-R}{2}\frac{I_0 t}{t_p^2}\frac{1}{h^2}\frac{(h+2\delta)+(h-2\delta)\mathrm{e}^{(h/\delta)}}{\mathrm{e}^{(h/\delta)}}\exp\left(-\frac{t}{t_p}\right) = 0. \tag{10}$$

For a sufficiently thin beam, assuming that the temperature increment varies as $\sin(pz)$ along the thickness direction, where $p = \pi/h$, thus, we obtain

$$K = \frac{1}{h^2}\int_{-h/2}^{h/2}\theta z\,\mathrm{d}z = \frac{1}{h^2 p^2}\left[\theta|_{-h/2}^{h/2} - z\frac{\partial \theta}{\partial z}|_{-h/2}^{h/2}\right] = -\frac{1}{p^2}\int_{-h/2}^{h/2}\frac{1}{h^2}\frac{\partial^2 \theta}{\partial z^2} z\,\mathrm{d}z. \tag{11}$$

Substituting Eq. (11) into Eq. (10) yields,

$$k\frac{\partial^2 K}{\partial x^2} - kp^2 K - \rho c_v \frac{\partial K}{\partial t} + \frac{T_0 \beta h}{12}\frac{\partial^3 w}{\partial x^2 \partial t} - \tau_0 \rho c_v \frac{\partial^2 K}{\partial t^2} + \frac{\tau_0 T_0 \beta h}{12}\frac{\partial^4 w}{\partial x^2 \partial t^2} + \frac{1-R}{2}\frac{I_0 t}{t_p^2 h}\frac{(1+2a)+(1-2a)\mathrm{e}^{(1/a)}}{\mathrm{e}^{(1/a)}}\exp\left(-\frac{t}{t_p}\right) = 0, \tag{12}$$

where $a = \delta/h$.

The governing equations for the coupled thermoelastic problem are as follows:

$$\begin{cases} \dfrac{Eh^2}{12}\dfrac{\partial^4 w}{\partial x^4} + \rho\dfrac{\partial^2 w}{\partial t^2} + \beta h \dfrac{\partial^2 K}{\partial x^2} = 0 \\ k\dfrac{\partial^2 K}{\partial x^2} - kp^2 K - \rho c_v \dfrac{\partial K}{\partial t} + \dfrac{T_0 \beta h}{12}\dfrac{\partial^3 w}{\partial x^2 \partial t} - \tau_0 \rho c_v \dfrac{\partial^2 K}{\partial t^2} + \dfrac{\tau_0 T_0 \beta h}{12}\dfrac{\partial^4 w}{\partial x^2 \partial t^2} \\ \qquad + \dfrac{1-R}{2}\dfrac{I_0 t}{t_p^2 h}\dfrac{(1+2a)+(1-2a)\mathrm{e}^{(1/a)}}{\mathrm{e}^{(1/a)}}\exp\left(-\dfrac{t}{t_p}\right) = 0. \end{cases} \tag{13}$$

3. Analytical solutions

In this manuscript, a beam with both ends simply supported and isothermal is considered. Eqs. (13) are solved using the combined finite sinusoidal Fourier and Laplace transformations (Refs. [17,18]). The boundary conditions are as follows:

$$\begin{aligned} &w|_{x=0} = w|_{x=L} = 0, \\ &\frac{\partial^2 w}{\partial x^2}|_{x=0} = \frac{\partial^2 w}{\partial x^2}|_{x=L} = 0, \\ &K|_{x=0} = K_{x=L} = 0. \end{aligned} \tag{14}$$

The initial conditions are:

$$\begin{aligned} w|_{t=0} &= 0, \quad \frac{\partial w}{\partial t}|_{t=0} = 0, \\ K|_{t=0} &= 0, \quad \frac{\partial K}{\partial t}|_{t=0} = 0. \end{aligned} \tag{15}$$

A finite sinusoidal Fourier transformation can be employed to solve Eqs. (13) as follows:

$$\begin{cases} w_m(m,t) = \int_0^L w(x,t)\sin\left(\frac{m\pi x}{L}\right)\mathrm{d}x, \\ K_m(m,t) = \int_0^L K(x,t)\sin\left(\frac{m\pi x}{L}\right)\mathrm{d}x. \end{cases} \tag{16}$$

The inverse of the transformations are as follows:

$$\begin{cases} w(x,t) = 2\sum_{m=1,3,\ldots}^{\infty} w_m(m,t)\sin\left(\frac{m\pi x}{L}\right), \\ K(x,t) = 2\sum_{m=1,3,\ldots}^{\infty} K_m(m,t)\sin\left(\frac{m\pi x}{L}\right). \end{cases} \tag{17}$$

Note that the boundary conditions for w and K are automatically satisfied.

By substituting Eqs. (16) into Eqs. (13), and implementing the initial conditions given by Eqs. (15), we obtain:

$$\begin{cases} \rho\frac{\partial^2 w_m}{\partial t^2} + \frac{Eh^2}{12}r^4 w_m - r^2\beta h K_m = 0 \\ k(r^2+p^2)K_m + \rho c_v\frac{\partial K_m}{\partial t} + \frac{T_0\beta h r^2}{12}\frac{\partial w_m}{\partial t} + \tau_0\rho c_v\frac{\partial^2 K_m}{\partial t^2} \\ \quad + \frac{\tau_0 T_0 \beta h r^2}{12}\frac{\partial^2 w_m}{\partial t^2} + \frac{1-R}{r}\frac{(1+2a)+(1-2a)\,\mathrm{e}^{(1/a)}}{\mathrm{e}^{(1/a)}}\frac{I_0 t}{t_p^2 h}\mathrm{e}^{(-t/t_p)} = 0, \end{cases} \tag{18}$$

$$\begin{aligned} &w_m|_{t=0} = 0, \\ &\frac{\partial w_m}{\partial t}|_{t=0} = 0, \\ &K_m|_{t=0} = 0 \\ &\frac{\partial K_m}{\partial t}|_{t=0} = 0, \end{aligned} \tag{19}$$

where $r = m\pi/L$, $m = 1,3,5,\ldots$.

Eqs. (18) can be simplified as follows:

$$\begin{cases} \frac{\partial^2 w_m}{\partial t^2} + A_1 w_m - A_2 K_m = 0, \\ A_3 K_m + A_4\frac{\partial K_m}{\partial t} + A_5\frac{\partial w_m}{\partial t} + A_6\frac{\partial^2 K_m}{\partial t^2} + A_7\frac{\partial^2 w_m}{\partial t^2} + A_8 t\,\mathrm{e}^{(-t/t_p)} = 0. \end{cases} \tag{20}$$

The coefficients in Eq. (20) are given by

$$\begin{aligned} &A_1 = \frac{Eh^2r^4}{12\rho}, \quad A_2 = \frac{r^2\beta h}{\rho}, \quad A_3 = k(r^2+p^2), \quad A_4 = \rho c_v, \quad A_5 = \frac{T_0\beta h r^2}{12}, \\ &A_6 = \tau_0\rho c_v, \quad A_7 = \frac{\tau_0 T_0\beta h r^2}{12}, \quad A_8 = \frac{1-R}{r}\frac{I_0}{t_p^2 h}\frac{(1+2a)+(1-2a)\mathrm{e}^{(1/a)}}{\mathrm{e}^{(1/a)}}. \end{aligned} \tag{21}$$

By applying Laplace transformation to Eqs. (20), we obtain

$$\begin{cases} s^2\tilde{w}_m + A_1\tilde{w}_m - A_2\tilde{K}_m = 0, \\ A_3\tilde{K}_m + A_4 s\tilde{K}_m + A_5 s\tilde{w}_m + A_6 s^2\tilde{K}_m + A_7 s^2\tilde{w}_m + \dfrac{A_8}{(s+1/t_p)^2} = 0. \end{cases} \tag{22}$$

By solving Eqs. (22), we obtain

$$\tilde{w}_m = \frac{b_0}{c_0 + c_1 s + c_2 s^2 + c_3 s^3 + c_4 s^4 + c_5 s^5 + c_6 s^6}, \tag{23}$$

where

$$\begin{aligned} b_0 &= -A_2 A_8 t_p^2, \\ c_0 &= A_1 A_3, \\ c_1 &= 2A_1 A_3 t_p + A_1 A_4 + A_2 A_5, \\ c_2 &= A_1 A_3 t_p^2 + 2(A_1 A_4 + A_2 A_5)t_p + A_1 A_6 + A_2 A_7 + A_3, \\ c_3 &= (A_1 A_4 + A_2 A_5)t_p^2 + 2(A_3 + A_1 A_6 + A_2 A_7)t_p + A_4, \\ c_4 &= (A_3 + A_1 A_6 + A_2 A_7)t_p^2 + 2A_4 t_p + A_6, \\ c_5 &= A_4 t_p^2 + 2A_6 t_p, \\ c_6 &= A_6 t_p^2. \end{aligned} \tag{24}$$

By inversing the Laplace transformation of Eq. (23), the deflection $w_m(m,t)$ is obtained as follows:

$$w_m(m,t) = \sum_{\alpha} \frac{b_0 e^{\alpha t}}{c_1 + 2c_2\alpha + 3c_3\alpha^2 + 4c_4\alpha^3 + 5c_5\alpha^4 + 6c_6\alpha^5}, \tag{25}$$

where α is the solutions of the following equation:

$$c_0 + c_1\alpha + c_2\alpha^2 + c_3\alpha^3 + c_4\alpha^4 + c_5\alpha^5 + c_6\alpha^6 = 0. \tag{26}$$

Substituting Eq. (25) into the first of Eqs. (17), the flexural deflection of the beam is obtained as follows:

$$w(x,t) = 2\sum_{m=1,3,\ldots}^{\infty} \sum_{\alpha} \frac{b_0 e^{\alpha t}}{c_1 + 2c_2\alpha + 3c_3\alpha^2 + 4c_4\alpha^3 + 5c_5\alpha^4 + 6c_6\alpha^5} \sin\left(\frac{m\pi x}{L}\right). \tag{27}$$

4. Analysis of the calculation results

In the present work, the effect of reference temperature on the vibration characteristics is studied. Based on Refs. [19–21], the material parameters of Si changes with temperature, as shown in Table 1. In the current calculation, the size of the beam is kept unchanged, i.e., $L/h = 10$, $b/h = 1/2$, $h = 10\,\mu m$. The relaxation time is $\tau_0 = 10^{-12}$ s, and the energy intensity of the laser pulse is $I_0 = 1000\,J/m^2$. For different values of a, which is related to the absorption depth, the beam absorbed different amount of energy and it vibrates in different manners.

Table 1
Material parameters for different reference temperatures

	E(GPa)	ρ(kg/m^3)	K(W/(m K))	C_v(J/kg K)	$\alpha(\times 10^{-6}\,K^{-1})$
$T_0 = 293$ K	165.9	2330	156	713	2.59
$T_0 = 500$ K	163.3	2325	80	832	3.614

Figs. 2 and 3 show the midspan deflection and temperature increment, respectively, for various values of $a = \delta/h$. The laser pulse duration and reference temperature are assumed to be $t_p = \tau_0 = 10^{-12}$ s and room temperature (i.e., $T_0 = 293$ K), respectively. Since the vibration of beam varies with time, in order to capture different vibration modes, the vibration curves are plotted for two time zones.

The non-Fourier effect can be clearly seen in Figs. 2 and 3, which show that in the beginning an abrupt increase of the deflection and temperature of the microscale beam occur and subsequently they reduce to zero. However, after a comparatively long lapse of time, they begin to vibrate periodically. Note that the sudden jump of deflection is much smaller than the vibration amplitude. Moreover, it is obvious that the abrupt increase of deflection decreases with increasing a, which is related to the energy absorption depth. This is because an increase of a will decrease the energy concentration in the beam. In addition, the deeper the absorption depth is, the more quickly the temperature distribution in the beam approaches uniformity. It is important to note that by varying the value of a, the vibration amplitude of deflection and temperature vary,

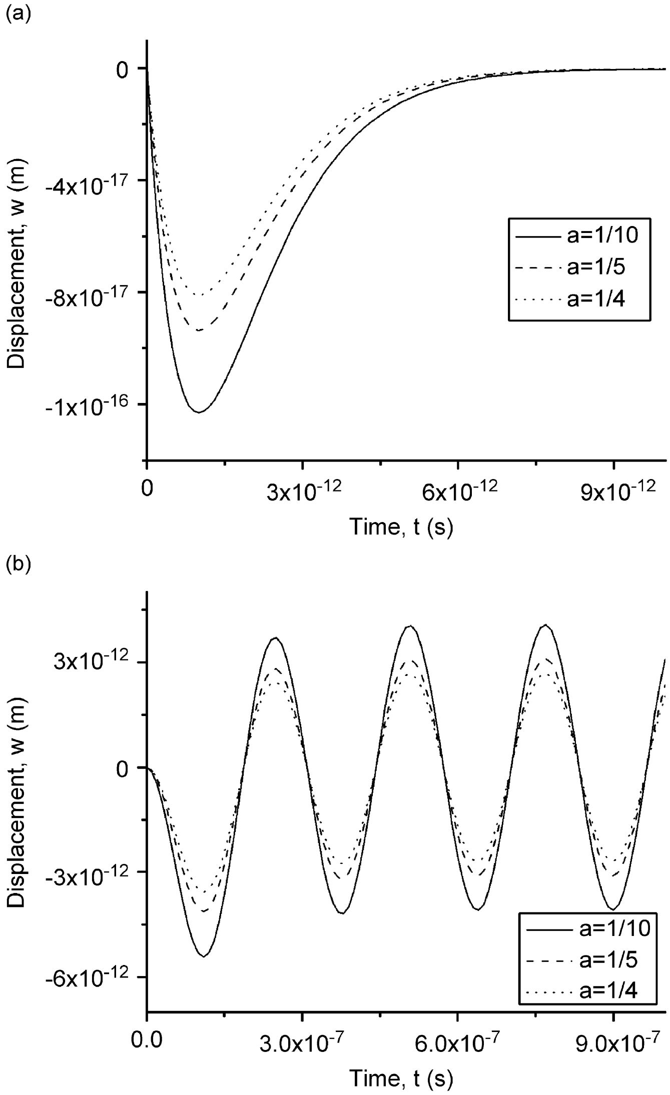

Fig. 2. Midspan deflection of a microscale beam for different values of $a = \delta/h$: (a) time range $t = 0–1 \times 10^{-11}$ s; (b) time range $t = 0–1 \times 10^{-6}$ s.

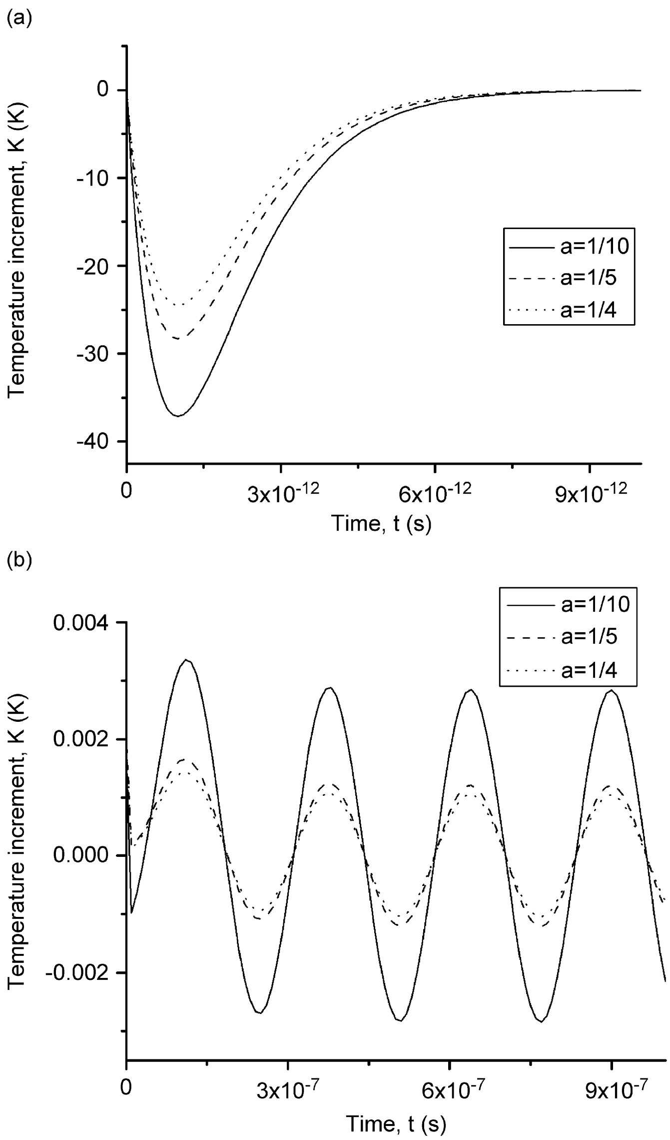

Fig. 3. Midspan temperature increment of a microscale beam for different values of $a = \delta/h$: (a) time range $t = 0–1 \times 10^{-11}$ s; (b) time range $t = 0–1 \times 10^{-6}$ s.

while the vibration frequency remains the same. This means that the laser pulse does not change the intrinsic frequency.

Figs. 4 and 5 show the plots of midspan deflection and temperature increment versus time, respectively, for two different values of reference temperature T_0. The laser pulse duration and energy absorption depth are assumed such that $t_p = \tau_0 = 10^{-12}$ s and $a = 1/10$, respectively. It can be seen that a microscale beam subjected to a higher reference temperature needs more time to reach the equilibrium state, i.e., the period is longer and, thus, the frequency is smaller. However, the vibration frequency seldom changes when the coupling effect between the strain rate and temperature field is ignored. This can be attributed to the effect of thermoelastic coupling, which shows some damping characteristics. It can be seen from Table 1 that the thermal parameters k, c_v and α change significantly with time, which lead to the change of vibration frequency.

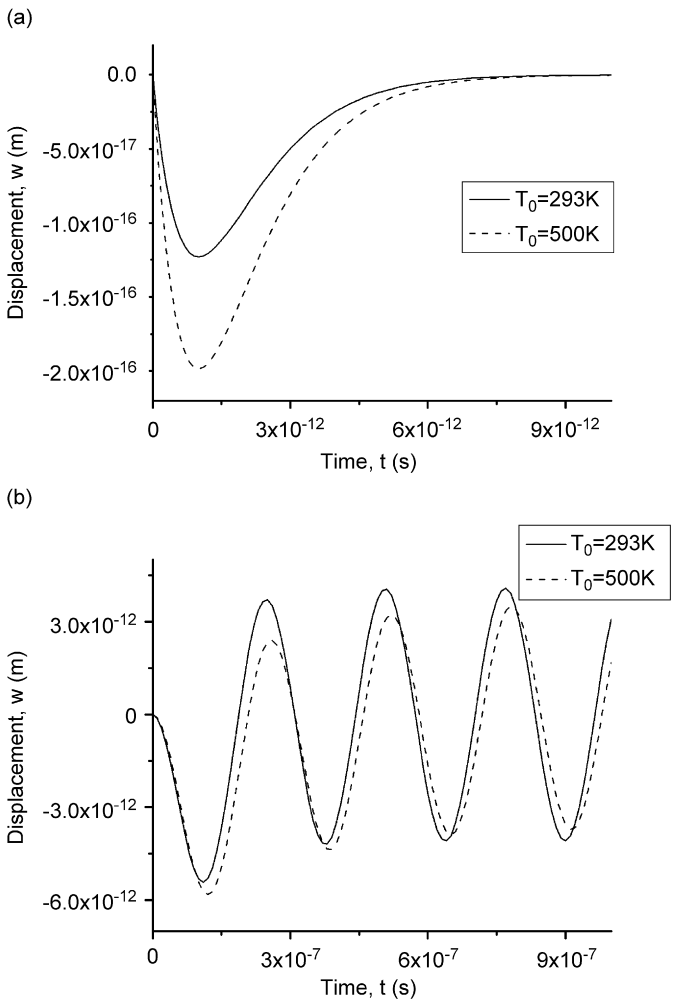

Fig. 4. Midspan deflection of a microscale beam for different reference temperatures T_0: (a) time range $t = 0\text{–}1 \times 10^{-11}$ s; (b) time range $t = 0\text{–}1 \times 10^{-6}$ s.

5. Conclusion

The vibration of a simply supported Euler–Bernoulli beam induced by a non-Gaussian form laser pulse has been studied. When a beam is heated by a laser pulse, the variation of temperature field and lateral vibration occur due to the thermoelastic coupling effect. The analytical solution to this problem has been obtained using the combined finite sinusoidal Fourier and Laplace transformation method.

In the present study, the non-Fourier effect of heat condution is accounted for and the thermal wave model is adopted. The effects of laser pulse energy absorption depth and reference temperature have been analyzed. It is important to note that after an abrupt increase of midspan deflection and temperature in the beginning, the beam reaches a quasi-steady vibration quickly, which clearly shows the non-Fourier effect.

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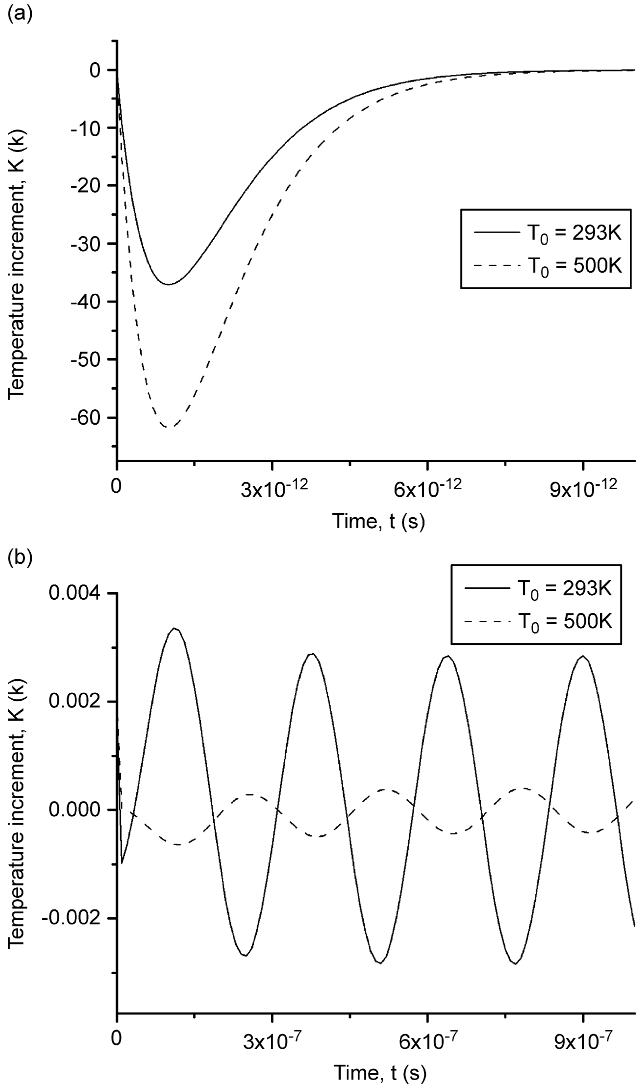

Fig. 5. Midspan temperature increment of a microscale beam for different reference temperatures T_0: (a) time range $t = 0$–1×10^{-11} s; (b) time range $t = 0$–1×10^{-6} s.

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