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QUASISTATIC THERMOVISCOELASTIC FIELDS IN AN INFINITE BICOMPOSITE CYLINDRICALLY ISOTROPIC PLATE

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With the most general assumptions (within the framework of classical thermomechanics) nonsteady temperature fields and thermoviscoelastic fields of displacements and stresses induced by them are constructed in an infinite bicomponent cylindrically isotropic plate. Examples of Biot–Maxwell, Biot–Kelvin, and Maxwell–Kelvin plates are presented.

1. Nonsteady Temperature Fields. The problem of the structure of a nonsteady temperature field in an infinite bicomponent cylindrically isotropic (c. is.) plate leads mathematically to the construction of the solution of a separate system of B-parabolic equations bounded in the domain $D = \{(t, r);\ t \geq 0,\ r \in I_2^+ = 0), R) \cup (R, \infty)\}$ [1]

$$\frac{1}{a_j^2}\frac{\partial T_j}{\partial t} + \varkappa_j^2 T_j - \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right) T_j = f_j(t,\ r),\ j = 1,\ 2, \tag{1}$$

with the initial conditions

$$T_1|_{t=0} = g_1(r),\ r \in (0, R),\ T_2|_{t=0} = g_2(r),\ r \in (R, \infty), \tag{2}$$

and the conditions of nonideal thermal contact [2]

$$\left[\left(r_{12}\frac{\partial}{\partial t} + 1\right) T_1 - T_2\right]\Big|_{r=R} = 0,\ \left(\lambda_1 \frac{\partial T_1}{\partial r} - \lambda_2 \frac{\partial T_2}{\partial r}\right)\Big|_{r=R} = 0. \tag{3}$$

The solution of problem (1)-(3) can be constructed by the method of integral Fourier–Bessel transformation on the polar axis with one conjugate point [3]. We omit the mathematical operations and find that the nonsteady temperature field in the plate under consideration is described by the functions (on the assumption that $k_{12}^2 \equiv a_2^2\kappa_2^2 - a_1^2\kappa_1^2 \geq 0$)

$$T_j(t,\ r) = \frac{1}{a_1^2}\int_0^R H_{j1}(t,\ r,\ \rho)\, g_1(\rho)\,\rho d\rho + \frac{1}{a_2^2}\int_R^\infty H_{j2}(t,\ r,\ \rho)\, g_2(\rho)\,\rho d\rho +$$
$$+ \int_0^t \left[\int_0^R H_{j1}(t-\tau,\ r,\ \rho) f_1(\tau,\ \rho)\,\rho d\rho + \int_R^\infty H_{j2}(t-\tau,\ r,\ \rho) f_2(\tau,\ \rho)\,\rho d\rho\right] d\tau, \tag{4}$$
$$j = 1,\ 2.$$

In formulas (4) we introduced into consideration the influence functions

$$H_{11}(t,\ r,\ \rho) = \frac{4\lambda_1\lambda_2}{\pi^2 R^2} e^{-a_2^2\varkappa_2^2 t}\int_0^\infty J_0\left(\frac{b_1}{a_1} r\right) J_0\left(\frac{b_1}{a_1}\rho\right) e^{-\lambda^2 t}\frac{\lambda d\lambda}{\omega(\lambda)},$$

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$$H_{12}(t, r, \rho) = \frac{2\lambda_2}{\pi R} \int_0^\infty J_0\left(\frac{b_1}{a_1} r\right) \Phi_0\left(\frac{b_2}{a_2}\rho, \lambda\right) e^{-\lambda^2 t} \frac{\lambda d\lambda}{\omega(\lambda)} e^{-a_2^2 \varkappa_2^2 t},$$

$$H_{21}(t, r, \rho) = \frac{2\lambda_1}{\pi R} \int_0^\infty J_0\left(\frac{b_1}{a_1} \rho\right) \Phi_0\left(\frac{b_2}{a_2} r, \lambda\right) e^{-\lambda^2 t} \frac{\lambda d\lambda}{\omega(\lambda)} e^{-a_2^2 \varkappa_2^2 t},$$

$$H_{22}(t, r, \rho) = e^{-a_2^2 \varkappa_2^2 t} \int_0^\infty \Phi_0\left(\frac{b_2}{a_2} r, \lambda\right) \Phi_0\left(\frac{b_2}{a^2}\rho, \lambda\right) e^{-\lambda^2 t} \frac{\lambda d\lambda}{\omega(\lambda)},$$

$$\omega(\lambda) = \omega_1^2(\lambda) + \omega_2^2(\lambda),$$

$$\omega_1(\lambda) = \lambda_2 \frac{b_2}{a_2} \Delta_1\left(\frac{b_1}{a_1} R\right) J_1\left(\frac{b_2}{a_2} R\right) - \frac{\lambda_1}{a_1} b_1 J_1\left(\frac{b_1}{a_1} R\right) J_0\left(\frac{b_2}{a_2} R\right),$$

$$\omega_2(\lambda) = \lambda_2 \frac{b_2}{a_2} \Delta_1\left(\frac{b_1}{a_1} R\right) N_1\left(\frac{b_2}{a_2} R\right) - \lambda_1 \frac{b_1}{a_1} J_1\left(\frac{b_1}{a_1} R\right) N_0\left(\frac{b_2}{a_2} R\right), \tag{5}$$

$$\Delta_1\left(\frac{b_1}{a_1} R\right) = J_0\left(\frac{b_1}{a_1} R\right) - r_{12} \frac{b_1}{a_1} J_0\left(\frac{b_1}{a_1} R\right), \quad b_1^2 = \lambda^2 + k_{21}^2, \quad b_2 = \lambda,$$

$$\Phi_0\left(\frac{b_2}{a_2} r, \lambda\right) = \omega_1(\lambda) N_0\left(\frac{b_2}{a_2} r\right) - \omega_2(\lambda) J_0\left(\frac{b_2}{a_2} r\right).$$

In the case of the inequality $k_{12}^2 \equiv a_1^2\kappa_1^2 - a_2^2\kappa_2^2 \ge 0$, $b_1 = \lambda$, $b_2^2 = \lambda^2 + k_{12}^2$ in formulas (5), and the factor $\exp(-a_2^2\kappa_2^2 t)$ is replaced by $\exp(-a_1^2\kappa_1^2 t)$.

We note that the parameters r_{12}, κ_1^2, κ_2^2 contained in the formulation of the problem (1)-(3) make it possible to pick out from the common structures (4), (5) all the cases most frequently used in engineering practice: a) the lateral surfaces of both components are heat-insulated ($\kappa_1^2 = \kappa_2^2 = 0$); b) the lateral surface of the first part of the plate is heat-insulated ($\kappa_1^2 = 0$), and through the lateral surface of the second part of the plate heat exchange occurs by Newton's law ($\kappa_2^2 \ne 0$, $b_2 = \lambda$, $b_1^2 = \lambda^2 + a_2^2\kappa_2^2$); c) through the lateral surface of the first part of the plate heat exchange occurs by Newton's law ($b_1 = \lambda$, $b_2^2 = \lambda^2 + a_1^2\kappa_1^2$ and $\exp(-a_2^2\kappa_2^2 t)$ are replaced by $\exp(-a_1^2\kappa_1^2 t)$) and the lateral surface of the second part is heat-insulated ($\kappa_2^2 = 0$). On the mating surface $r = R$ ideal themal contact ($r_{12} = 0$) as well as nonideal one ($r_{12} \ne 0$) can be effected.

2. Quasistatic Thermoviscoelastic Fields. On the assumption that a bicomponent c. is. plate is elastic and free of external load, the quasistatic stress field induced by the nonsteady temperature field (4) is described by the functions [4]

$$\sigma_{rr,j}(r, t) = \bar{E}_j\left[\left(\frac{d}{dr} + \frac{\nu_j}{r}\right) u_j - (1+\nu_j)\alpha_{tj} T_j(t, r)\right], \quad \bar{E}_j = \frac{E_j}{1-\nu_j^2},$$

$$\sigma_{\varphi\varphi,j}(r, t) = \bar{E}_j\left[\left(\nu_j \frac{d}{dr} + \frac{1}{r}\right) u_j - (1+\nu_j)\alpha_{tj} T_j(t, r)\right], \quad j = 1, 2. \tag{6}$$

Here the functions $u_j(r, t)$ are bounded on the set I_1^+ by the solution of the separate system of inhomogeneous Euler equations

$$\left(\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} - \frac{1}{r^2}\right) u_j = (1+\nu_j)\alpha_{tj} \frac{\partial T_j}{\partial r}(t, r), \quad j = 1, 2, \tag{7}$$

according to the ideal conditions of mechanical contact on the mating surface:

$$[u_1(r, t) - u_2(r, t)]|_{r=R} = 0,$$

$$\left[\left(\frac{d}{dr} + \frac{\nu_1}{r}\right) u_1 - \mu_{21}\left(\frac{d}{dr} + \frac{\nu_2}{r}\right) u_2\right]\Big|_{r=R} = g_{12}(t). \tag{8}$$

Here the following notation is introduced:

$$\mu_{21} = \frac{\bar{E}_2}{\bar{E}_1} = \frac{E_2}{E_1}\frac{1-\nu_1^2}{1-\nu_2^2},$$

$$g_{12}(t) = \alpha_{t1}(1+\nu_1)T_1(t, R) - \mu_{21}\alpha_{t2}(1+\nu_2)T_2(t, R).$$

The elastic solution of problem (6)-(8) was constructed by the method of Cauchy functions:

$$u_1(r, t) = A_{11}\frac{r}{R^2}\int_0^R T_1(t, \rho)\rho d\rho - \frac{(1+\nu_1)\alpha_{t1}}{R^2} \times$$
$$\times\left[\frac{r^2-R^2}{r}\int_0^R T_1(t, \rho)\rho d\rho + r\int_r^R T_1(t, \rho)\rho d\rho\right],$$
$$A_{11} = \frac{2\alpha_{t1}(1+\nu_1)}{1+\nu_1+\mu_{21}(1-\nu_2)},$$
$$u_2(r, t) = A_{11}\frac{1}{r}\int_0^R T_1(t, \rho)\rho d\rho + (1+\nu_2)\alpha_{t2}\frac{1}{r}\int_R^r T_2(t, \rho)\rho d\rho, \tag{9}$$
$$\sigma_{rr,1}(r, t) = \frac{E_1}{1-\nu_1}\left\{\frac{A_{11}}{R^2}\int_0^R T_1(t, \rho)\rho d\rho +\right.$$
$$\left.+\frac{(1+\nu_1)\alpha_{t1}}{R^2}\left[\left(1+\frac{1-\nu_1}{1+\nu_1}\frac{R^2}{r^2}\right)\int_0^r T_1(t, \rho)\rho d\rho + \int_r^R T_1(t, \rho)\rho d\rho\right]\right\},$$
$$\sigma_{\varphi\varphi,1}(r, t) = \frac{E_1}{1-\nu_1}\left\{\frac{A_{11}}{r^2}\int_0^R T_1(t, \rho)\rho d\rho -\right.$$
$$-\frac{(1+\nu_1)\alpha_{t1}}{R^2}\left[\left(1-\frac{1-\nu_1}{1+\nu_1}\frac{R^2}{r^2}\right)\int_0^r T_1(t, \rho)\rho d\rho +\right.$$
$$\left.\left.+\int_r^R T_1(t, \rho)\rho d\rho - \alpha_{t1}(1-\nu_1)T_1(t, r)\right]\right\},$$
$$\sigma_{rr,2}(r, t) = -\frac{E_2}{1+\nu_2}\left\{\frac{A_{11}}{r^2}\int_0^R T_1(t, \rho)\rho d\rho +\right.$$
$$\left.+\frac{\alpha_{t2}(1+\nu_2)}{r^2}\int_R^r T_2(t, \rho)\rho d\rho\right\},$$
$$\sigma_{\varphi\varphi,2}(r, t) = \frac{E_2}{1+\nu_2}\left\{\frac{A_{11}}{r^2}\int_0^R T_1(t, \rho)\rho d\rho +\right.$$
$$\left.+\frac{\alpha_{t2}(1+\nu_2)}{r^2}\int_R^r T_2(t, \rho)\rho d\rho - \alpha_{t2}(1+\nu_2)T_2(t, r)\right\}.$$

We assume now that the bicomponent infinite c. is. plate is viscoelastic. We use the method of elastic–viscoelastic analogy [5].

We determine the functions

$$A_{12}(\nu_1, \nu_2, E_1, E_2) = \alpha_{t1}(1+\nu_1)\frac{1-\nu_1-\mu_{21}(1-\nu_2)}{1+\nu_1+\mu_{21}(1-\nu_2)},$$
$$B_{11}(\nu_1, \nu_2, E_1, E_2) = E_1 A_{12}\frac{1}{1-\nu_1} =$$
$$= \alpha_{t1}E_1\frac{1+\nu_1}{1-\nu_1}\frac{1-\nu_1-\mu_{21}(1-\nu_2)}{1+\nu_1+\mu_{21}(1-\nu_2)},$$
$$B_{21}(\nu_1, \nu_2, E_1, E_2) = 2\alpha_{t1}E_2\frac{1+\nu_1}{1+\nu_2}\frac{1}{1+\nu_1+\mu_{21}(1-\nu_2)}.$$

In Laplace transforms we have

$$u_1^*(r,\ p) = A_{12}\frac{r}{R^2}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho + \alpha_{t1}(1+\nu_1)\frac{1}{r}\int_0^r T_1^*(p,\ \rho)\,\rho d\rho,$$

$$u_2^*(r,\ p) = A_{11}\frac{1}{r}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho + \alpha_{t2}(1+\nu_2)\frac{1}{r}\int_R^r T_2^*(p,\ \rho)\,\rho d\rho$$

$$\sigma_{rr,1}^*(r,\ p) = B_{11}\frac{1}{R^2}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho - \alpha_{t1}E_1\frac{1}{r^2}\int_0^r T_1^*(p,\ \rho)\,\rho d\rho,$$

$$\sigma_{\varphi\varphi,1}^*(r,\ p) = B_{11}\frac{1}{r^2}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho +$$

$$+\alpha_{t1}E_1\frac{1}{r^2}\int_0^r T_1^*(p,\ \rho)\,\rho d\rho - \alpha_{t1}E_1T_1^*(p,\ r),$$

$$\sigma_{rr,2}^*(r,\ p) = -B_{21}\frac{1}{r^2}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho - \alpha_{t2}E_2\frac{1}{r^2}\int_R^r T_2^*(p,\ \rho)\,\rho d\rho,$$

$$\sigma_{\varphi\varphi,2}^*(r,\ p) = B_{21}\frac{1}{r^2}\int_0^R T_1^*(p,\ \rho)\,\rho d\rho +$$

$$+\alpha_{t2}E_2\frac{1}{r^2}\int_R^r T_2^*(p,\ \rho)\,\rho d\rho - \alpha_{t2}E_2T_2^*(p,\ r).$$

In accordance with the elastic—viscoelastic analogy we obtain

$$u_1^{v*}(r,\ p) = \frac{r}{R^2}\int_0^R A_{12}^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho +$$

$$+\alpha_{t1}\frac{1}{r}\int_0^r (1+\nu_1^*(p))\,T_1^*(p,\ \rho)\,\rho d\rho,$$

$$u_2^{v*}(r,\ p) = \frac{1}{r}\int_0^R A_{11}^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho +$$

$$+\alpha_{t2}\frac{1}{r}\int_R^r (1+\nu_2^*(p))\,T_2^*(p,\ \rho)\,\rho d\rho,$$

$$A_{1j}^*(p) \equiv A_{1j}^*(\nu_1^*(p),\ \nu_2^*(p),\ E_1^*(p),\ E_2^*(p)),$$

$$B_{2j}^*(p) \equiv B_{2j}^*(\nu_1^*(p),\ \nu_2^*(p),\ E_1^*(p),\ E_2^*(p)),\quad j = 1,\ 2,$$

$$\sigma_{rr,1}^{v*}(r,\ p) = \frac{1}{R^2}\int_0^R B_{11}^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho -$$

$$-\alpha_{t1}\frac{1}{r^2}\int_0^r E_1^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho, \qquad (10)$$

$$\sigma_{\varphi\varphi,1}^{v*}(r,\ p) = \frac{1}{R^2}\int_0^R B_{11}^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho +$$

$$+\alpha_{t1}\frac{1}{r^2}\int_0^R E_1^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho - \alpha_{t1}E_1^*(p)\,T_1^*(p,\ r),$$

$$\sigma_{rr,2}^{v*}(r,\ p) = -\frac{1}{r^2}\int_0^R B_{21}^*(p)\,T_1^*(p,\ \rho)\,\rho d\rho -$$

$$-\alpha_{t2}\frac{1}{r^2}\int_R^r E_2^*(p)\,T_2^*(p,\ \rho)\,\rho d\rho,$$

$$\sigma_{\varphi\varphi,2}^{v*}(r, p) = \frac{1}{r^2}\int_0^R B_{21}^*(p)T_1^*(p, \rho)\rho d\rho +$$

$$+\alpha_{t2}\frac{1}{r^2}\int_R^r E_2^*(p)T_2^*(p, \rho)d\rho - \alpha_{t2}E_2^*(p)T_2^*(p, r).$$

Here $u_j^v(r, t)$ are functions describing the viscoelastic field of displacements in the plate under consideration; $\sigma_{rr,j}^v(r, t)$, $\sigma_{\phi\phi,j}^v(r, t)$ are functions describing the viscoelastic stress field in that plate.

We bring into consideration the operator functions

$$A_{1j}\left(t, \frac{\partial}{\partial t}\right) = \frac{1}{2\pi i}\int_\gamma A_{1j}^*(p)e^{pt}dp,$$

$$E_j\left(t, \frac{\partial}{\partial t}\right) = \frac{1}{2\pi i}\int_\gamma E_j^*(p)e^{pt}dp,$$

$$B_{2j}\left(t, \frac{\partial}{\partial t}\right) = \frac{1}{2\pi i}\int_\gamma B_{2j}^*(p)e^{pt}dp, \tag{11}$$

$$C_j\left(t, \frac{\partial}{\partial t}\right) = \frac{1}{2\pi i}\int_\gamma (1+\nu_j^*(p))e^{pt}dp, \quad j = 1, 2,$$

where γ is the Bromwich contour [6].

Reverting in formulas (10) to the original, we obtain functions describing in the infinite bicomponent c. is. plate the quasistatic thermoviscoelastic field of displacements and stresses:

$$u_1^v(r, t) = \frac{r}{R^2}\int_0^R A_{12}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho + \alpha_{t1}\frac{1}{r}\int_0^r C_1\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho,$$

$$u_2^v(r, t) = \frac{1}{r}\int_0^R A_{11}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho +$$

$$+\alpha_{t2}\frac{1}{r}\int_R^r C_2\left(t, \frac{\partial}{\partial t}\right)_t^* T_2(t, \rho)\rho d\rho,$$

$$\sigma_{rr,1}^v(r, t) = \frac{1}{R^2}\int_0^R B_{11}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho -$$

$$-\alpha_{t1}\frac{1}{r^2}\int_0^r E_1\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho,$$

$$\sigma_{\varphi\varphi,1}^v(r, t) = \frac{1}{R^2}\int_0^R B_{11}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho + \tag{12}$$

$$+\alpha_{t1}\frac{1}{r^2}\int_0^r E_1\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho - \alpha_{t1}E_1\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, r),$$

$$\sigma_{rr,2}^v(r, t) = -\frac{1}{r^2}\int_0^R B_{21}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho -$$

$$-\alpha_{t2}\frac{1}{r^2}\int_R^r E_2\left(t, \frac{\partial}{\partial t}\right)_t^* T_2(t, \rho)\rho d\rho,$$

$$\sigma_{\varphi\varphi,2}^v(r, t) = \frac{1}{r^2}\int_0^R B_{21}\left(t, \frac{\partial}{\partial t}\right)_t^* T_1(t, \rho)\rho d\rho +$$

$$+\alpha_{t2}\frac{1}{r^2}\int_R^r E_2\left(t, \frac{\partial}{\partial t}\right)_t^* T_2(t, \rho)\rho d\rho - \alpha_{t2}E_2\left(t, \frac{\partial}{\partial t}\right)_t^* T_2(t, r).$$

Here, $(\overset{*}{t})$ is the convolution of the operator function with respect to the argument t [7].

Let us consider Biot's, Maxwell's, and Kelvin's materials which are the most widely used ones in engineering practice.

Example 1. Biot–Maxwell Plate. According to [4, 5] we have

$$\nu_1^*(p) = \nu_{10} = \text{const}, \quad E_1^*(p) = E_{10}\left(1 - \frac{\varepsilon}{p+\varepsilon}\right), \quad E_{10} = \text{const},$$

$$\nu_2^*(p) = a_1 \frac{p+a_2}{p+a_3}, \quad E_2^*(p) = a_4 \frac{p}{p+a_3}, \quad a_1 = \frac{2(\varepsilon_1 - 1)}{1+2\varepsilon_1},$$

$$a_2 = \frac{\varepsilon_1}{\theta(\varepsilon_1 - 1)}, \quad a_3 = \frac{2\varepsilon_1}{\theta(1+2\varepsilon_1)}, \quad a_4 = \frac{6\varepsilon_1 G_{20}}{1+2\varepsilon_1},$$

$$\varepsilon_1 = \frac{1+\nu_{20}}{1-2\nu_{20}}, \quad A_{11}^*(p) = c_1\left(1 + \frac{b_2}{1+b_1}\right), \quad A_{12}^* = c_2\left(1 + \frac{b_3 - b_1}{p+b_1}\right)$$

$$c_1 = \frac{2\alpha_{t1} E_{10}(1+a_1)}{E_{10}(1+a_1) + a_4(1-\nu_{10})}, \quad B_{11}^*(p) = \frac{c_2 E_{10}}{1-\nu_{10}}\left\{1 - \varepsilon\frac{b_3-\varepsilon}{b_1-\varepsilon} \times \right.$$

$$\left.\times \frac{1}{p+\varepsilon} + \frac{b_1(b_3-b_1)}{(b_1-\varepsilon)(p+b_1)}\right\}, \quad B_{21}^*(p) = \frac{c_1 a_4}{1+a_1}\left(1 - \frac{b_1}{p+b_1}\right),$$

$$c_2 = \alpha_{t1}(1-\nu_{10})\frac{E_{10}(1+a_1) - a_4(1+\nu_{10})}{E_{10}(1+a_1) + a_4(1-\nu_{10})},$$

$$b_1 = \frac{E_{10}(a_3 + a_1 a_2) + a_4(1-\nu_{10})\varepsilon}{E_{10}(1+a_1) + a_4(1-\nu_{10})}, \quad b_2 = \frac{a_3 + a_1 a_2}{1+a_1} - b_1,$$

$$E_2^* = a_4\left(1 - \frac{a_3}{p+a_3}\right), \quad 1 + \nu_2^* = 1 + a_1 + \frac{a_1(a_2 - a_3)}{p+a_3},$$

$$b_3 = \frac{E_{10}(a_3 + a_1 a_2) - a_4(1+\nu_{10})\varepsilon}{E_{10}(1+a_1) - a_4(1+\nu_{10})}.$$

The operator functions for an infinite bicomponent c.is, Biot–Maxwell plate are calculated by formulas (11):

$$A_{11} = c_1[\delta(t) + b_2 e^{-b_1 t}], \quad A_{12} = c_2[\delta(t) + (b_3 - b_1)e^{-b_1 t}],$$

$$B_{11} = \frac{c_2 E_{10}}{1-\nu_{10}}\left\{\delta(t) - \varepsilon\frac{b_3-\varepsilon}{b_1-\varepsilon}e^{-\varepsilon t} + \frac{b_1(b_3-b_1)}{b_1-\varepsilon}e^{-b_1 t}\right\},$$

$$B_{21} = \frac{c_1 a_4}{1+a_1}[\delta(t) - b_1 e^{-b_1 t}], \quad E_2 = a_4[\delta(t) - a_3 e^{-a_3 t}],$$

$$c_1 \equiv 1 + \nu_1 = (1+\nu_{10})\delta(t), \quad c_2 \equiv 1 + \nu_2 = (1+a_1)\delta(t) +$$

$$+ a_1(a_2 - a_3)e^{-a_3 t}, \quad E_1 = E_{10}[\delta(t) - \varepsilon e^{-\varepsilon t}].$$

In accordance with formulas (12) the quasistatic thermoviscoelastic field of displacements in a Biot–Maxwell plate is described by the functions

$$u_1^v(r, t) = c_2 \frac{r}{R^2}\int_0^R T_1(t, \rho)\rho d\rho + \alpha_{t1}(1+\nu_{10})\frac{1}{r}\int_0^r T_1(t, \rho)\rho d\rho +$$

$$+ c_2(b_3 - b_1)\frac{r}{R^2}\int_0^t\int_0^R e^{-b_1(t-\tau)}T_1(\tau, \rho)\rho d\rho d\tau,$$

$$u_2^v(r, t) = c_1\frac{1}{r}\int_0^R T_1(t, \rho)\rho d\rho + \alpha_{t2}(1+a_1)\frac{1}{r}\int_R^r T_2(t, \rho)\rho d\rho + \tag{13}$$

$$+ c_1 b_2 \frac{1}{r}\int_0^t\int_0^R e^{-b_1(t-\tau)}T_1(\tau, \rho)\rho d\rho d\tau + \alpha_{t2}a_1(a_2 - a_3)\frac{1}{r}\int_0^t\int_R^r e^{-a_3(t-\tau)}T_2(\tau, \rho)\rho d\rho d\tau.$$

Hence follows that the viscoelastic field of displacements is the sum of the thermoelastic field of displacements and of the field of displacements originating on account of the viscosity of the material. In the structure of the quasistatic thermoviscoelastic field of displacements in the Biot plate (the first part of the bicomponent plate) the temperature field of the Maxwell plate (the second part of the bicomponent plate) does not participate.

The quasistatic thermoviscoelastic stress field in the Biot-Maxwell plate under consideration is described by the functions

$$\sigma^v_{rr,1}(r,\ t) = \frac{c_2 E_{10}}{1-\nu_{10}} \frac{1}{R^2} \int_0^R T_1(t,\ \rho)\rho d\rho - \alpha_{t1} E_{10} \frac{1}{r^2} \int_0^r T_1(t,\ \rho)\rho d\rho +$$

$$+ \frac{c_2 E_{10}}{R^2(1-\nu_{10})} \int_0^t \int_0^R \Big[-\varepsilon \frac{b_3-\varepsilon}{b_1-\varepsilon} e^{-\varepsilon(t-\tau)} +$$

$$+ b_1 \frac{b_3-b_1}{b_1-\varepsilon} e^{-b_1(t-\tau)} \Big] T_1(\tau,\ \rho)\rho d\rho d\tau +$$

$$+ \alpha_{t1} E_{10} \varepsilon \frac{1}{r^2} \int_0^t \int_0^r e^{-\varepsilon(t-\tau)} T_1(\tau,\ \rho)\rho d\rho d\tau,$$

$$\sigma^v_{\varphi\varphi,1}(r,\ t) = \sigma^v_{rr,1}(r,\ t) + 2\alpha_{t1} E_{10} \frac{1}{r^2} \Big[\int_0^r T_1(t,\ \rho)\rho d\rho -$$

$$- \varepsilon \int_0^t \int_0^r e^{-\varepsilon(t-\tau)} T_1(\tau,\ \rho)\rho d\rho \Big] - \alpha_{t1} E_{10} \Big[T_1(t,\ r) - \varepsilon \int_0^t e^{-\varepsilon(t-\tau)} T_1(\tau,\ r) d\tau \Big], \tag{14}$$

$$\sigma^v_{rr,2}(r,\ t) = -\frac{c_1 a_4}{1+a_1} \frac{1}{r^2} \Big[\int_0^R T_1(t,\ \rho)\rho d\rho -$$

$$- b_1 \int_0^t \int_0^R e^{-b_1(t-\tau)} T_1(\tau,\ \rho)\rho d\rho d\tau \Big] - \alpha_{t2} a_4 \frac{1}{r^2} \Big[\int_R^r T_2(t,\ \rho)\rho d\rho -$$

$$- a_3 \int_0^t \int_R^r e^{-a_3(t-\tau)} T_2(\tau,\ \rho)\rho d\rho d\tau \Big], \quad \sigma^v_{\varphi\varphi,2}(r,\ t) = -\sigma^v_{rr,2}(r,\ t) -$$

$$- \alpha_{t2} a_4 \Big[T_2(t,\ r) - a_3 \int_0^t e^{-a_3(t-\tau)} T_2(\tau,\ r) d\tau \Big].$$

Hence follows: 1) in the Biot plate the thermoviscoelastic stress field is induced by the temperature field itself; 2) the quasistatic thermoviscoelastic stress field in the Biot-Maxwell plate forms as a result of the superposition of the thermoelastic stress field and the stress field arising on account of the viscosity of the material.

Example 2. Biot-Kelvin Plate. In accordance with [4, 5] we have

$$\nu_1^*(p) = \nu_{10} = \text{const}, \quad E_1^* = E_{10}\left(1 - \frac{\varepsilon}{p+\varepsilon}\right), \quad E_{10} = \text{const},$$

$$\nu_2^*(p) = -1 + \frac{\dfrac{3a_0}{\theta}}{p + \dfrac{1+2a_0}{\theta}}, \quad a_0 = \frac{1+\nu_{20}}{1-2\nu_{20}}.$$

$$E_2^*(p) = \frac{3E_{20}}{1-2\nu_{20}} \left(1 - \frac{\dfrac{2a_0}{\theta}}{p + \dfrac{1+2a_0}{\theta}} \right).$$

According to formulas (11) we obtain

$$A_{11} = \frac{2\alpha_{t1} E_{10}(1+\nu_{20})}{\theta E_{20}(1-\nu_{10}) b_2} e^{-b_1 t} [b_2 \operatorname{ch} b_2 t - b_1 \operatorname{sh} b_2 t],$$

$$A_{12} = -\alpha_{t1}\delta(t) + \frac{\alpha_{t1}E_{10}(1+\nu_{20})(2-\nu_{10})}{b_2\theta E_{20}(1-\nu_{10})} e^{-b_1 t}(b_2 \operatorname{ch} b_2 t - b_1 \operatorname{sh} b_2 t) =$$

$$= -\alpha_{t1}\delta(t) + \left(1 - \frac{1}{2}\nu_{10}\right) A_{11}, \quad B_{11} = -\frac{\alpha_{t1}}{1-\nu_{10}} E_1 +$$

$$+ \frac{\alpha_{t1}E_{10}^2(1+\nu_{20})(2-\nu_{10})}{\theta E_{20}(1-\nu_{10})^2[(\varepsilon - b_1^2) - b_2^2]} \Big\{\varepsilon^2 e^{-\varepsilon t} + e^{-b_1 t}\Big[((b_1^2 + b_2^2)\varepsilon +$$

$$+ b_1(b_2^2 - b_1^2))\frac{\operatorname{sh} b_2 t}{b_2} - (2b_1\varepsilon + b_2^2 - b_1^2)\operatorname{ch} b_2 t\Big]\Big\} \equiv$$

$$\equiv -\frac{\alpha_{t1}E_{10}}{1-\nu_{10}}\delta(t) + m(t), \quad B_{21} = \frac{\theta E_{20}}{1+\nu_{20}} A_{11},$$

$$E_1 = E_{10}[\delta(t) - \varepsilon e^{-\varepsilon t}], \quad E_2 = \frac{3E_{20}}{1-2\nu_{20}}\left[\delta(t) - \frac{2a_0}{\theta} e^{-(1+2a_0)\frac{t}{\theta}}\right],$$

$$c_1 = (1+\nu_{10})\delta(t), \; c_2 = \frac{3a_0}{\theta} e^{-(1+2a_0)\frac{t}{\theta}}, \; 2b_1 = \varepsilon + \frac{1}{\theta} + \frac{E_{10}(1+\nu_{20})}{\theta E_{20}(1-\nu_{10})},$$

$$2b_2 = \sqrt{\left(\varepsilon + \frac{1}{\theta}\right)^2 + 2\left(\varepsilon + \frac{1}{\theta}\right)\frac{E_{10}(1+\nu_{20})}{\theta E_{20}(1-\nu_{10})} + \frac{E_{10}^2(1+\nu_{20})^2}{\theta^2 E_{20}^2(1-\nu_{10})^2}}.$$

According to formulas (12), the quasistatic thermoviscoelastic field in the Biot-Kelvin plate is described by the functions

$$u_1^v(r, t) = -\alpha_{t1}\frac{r}{R^2}\int_0^R T_1(t, \rho)\rho d\rho + \alpha_{t1}\frac{1}{r}(1+\nu_{10})\int_0^r T_1(t, \rho)\rho d\rho +$$

$$+ \left(1 - \frac{1}{2}\nu_{10}\right)\frac{r}{R^2}\int_0^t\int_0^R A_{11}(t-\tau)T_1(\tau, \rho)\rho d\rho d\tau,$$

$$u_2^v(r, t) = \frac{1}{r}\int_0^t\int_0^R A_{11}(t-\tau)T_1(\tau, \rho)\rho d\rho +$$

$$+ \alpha_{t2}\frac{3a_0}{\theta r}\int_0^t\int_R^r e^{-\frac{1+2a_0}{\theta}(t-\tau)} T_2(\tau, \rho)\rho d\rho d\tau,$$

$$\sigma_{rr,1}^v(r, t) = -\frac{\alpha_{t1}E_{10}}{1-\nu_{10}}\frac{1}{R^2}\int_0^R T_1(t, \rho)\rho d\rho - \alpha_{t1}E_{10}\frac{1}{r^2}\int_0^r T_1(t, \rho)\rho d\rho +$$

$$+ \frac{1}{R^2}\int_0^t\int_0^R m(t-\tau)T_1(\tau, \rho)\rho d\rho + \alpha_{t1}E_{10}\varepsilon\frac{1}{r^2}\int_0^t\int_0^r e^{-\varepsilon(t-\tau)}T_1(\tau, \rho)\rho d\rho,$$

$$\sigma_{\varphi\varphi,1}^v(r, t) = -\frac{\alpha_{t1}E_{10}}{1-\nu_{10}}\frac{1}{R^2}\int_0^R T_1(t, \rho)\rho d\rho + \alpha_{t1}E_{10}\frac{1}{r^2}\int_0^r T_1(t, \rho)\rho d\rho -$$

$$- \alpha_{t1}E_{10}T_1(t, r) + \frac{1}{R^2}\int_0^t\int_0^R m(t-\tau)T_1(\tau, \rho)\rho d\rho - \alpha_{t1}E_{10}\varepsilon\frac{1}{r^2} \times$$

$$\times \int_0^t\int_0^r e^{-\varepsilon(t-\tau)}T_1(\tau, \rho)\rho d\rho d\tau + \alpha_{t1}E_{10}\varepsilon\int_0^t e^{-\varepsilon(t-\tau)}T_1(\tau, r)d\tau, \qquad (15)$$

$$\sigma_{rr,2}^v(r, t) = \frac{\theta E_{20}}{1+\nu_{20}}\frac{1}{r^2}\int_0^t\int_0^R A_{11}(t-\tau)T_1(\tau, \rho)\rho d\rho -$$

$$- \frac{3E_{20}\alpha_{t2}}{1-2\nu_{20}}\int_R^r T_2(t, \rho)\rho d\rho +$$

$$+ \frac{6a_0\alpha_{t2}E_{20}}{\theta(1-2\nu_{20})}\frac{1}{r^2}\int_0^t\int_R^r e^{-\frac{1+2a_0}{\theta}(t-\tau)} T_2(\tau, \rho)\rho d\rho d\tau,$$

$$\sigma^{v}_{\varphi\varphi,2}(r,\ t) = \frac{\theta E_{10}}{1+\nu_{20}}\frac{1}{r^2}\int\limits_0^t\int\limits_0^R A_{11}(t-\tau)\,T_1(\tau,\ \rho)\,\rho d\rho +$$

$$+\frac{3\alpha_{t2}E_{20}}{1-2\nu_{20}}\frac{1}{r^2}\left[\int\limits_R^r T_2(t,\ \rho)\,\rho d\rho - \frac{2a_0}{\theta}\int\limits_0^t\int\limits_R^r e^{-\frac{1+2a_0}{\theta}(t-\tau)}\,T_2(\tau,\ \rho)\,\rho d\rho d\tau\right] -$$

$$-\frac{3\alpha_{t2}E_{20}}{1-2\nu_{20}}\left(T_2(t,\ r) - \frac{2a_0}{\theta}\int\limits_0^t e^{-\frac{1+2a_0}{\theta}(t-\tau)}\,T_2(\tau,\ r)\,d\tau\right).$$

The deductions from formula (15) are the same as the deductions for the Biot-Maxwell plate.

Example 3. Maxwell-Kelvin plate. We have [5]:

$$\nu_1^* = a_1\frac{p+a_2}{p+a_3},\quad E_1^*(p) = a_4\frac{p}{p+a_3},\quad a_1 = \frac{2(\varepsilon_1-1)}{1+2\varepsilon_1},$$

$$a_2 = \frac{\varepsilon_1}{\theta_1(\varepsilon_1-1)},\quad a_3 = \frac{2\varepsilon_1}{\theta_1(1+2\varepsilon_1)},\quad a_4 = \frac{6\varepsilon_1 G_{10}}{1+2\varepsilon_1},$$

$$\varepsilon_1 = \frac{1+\nu_{10}}{1-2\nu_{10}},\quad \nu_2^* = -1 + \frac{\dfrac{3a_0}{\theta_2}}{p+\dfrac{1+2a_0}{\theta_2}},$$

$$E_2^* = \frac{3E_{20}}{1-2\nu_{20}}\left(1 - \frac{\dfrac{2a_0}{\theta_2}}{p+\dfrac{1+2a_0}{\theta_2}}\right),\quad a_0 = \frac{1+\nu_{20}}{1-2\nu_{20}}.$$

According to formulas (11) we obtain:

$$A_{11} = 2\,\frac{b_1}{b_4}\,e^{-b_2 t}\,\mathrm{sh}\,b_4 t,\quad A_{12} = -\alpha_{t1}(1+a_1)\Big\{\delta(t) +$$

$$+\frac{a_3^2-\gamma_1 a_3+\gamma_2}{(a_3+p_1)(a_3+p_2)}\,e^{-a_3 t} + \left[\frac{(\gamma_1-2b_2)\,p_1+\gamma_2-b_3}{p_1-p_2} +\right.$$

$$\left.+\frac{p_1^2+\gamma_1 p_1+\gamma_2}{(p_1+a_3)(p_1-p_2)}\right]e^{p_1 t} - \left[\frac{(\gamma_1-2b_2)\,p_2+\gamma_2-b_3}{p_1-p_2} +\right.$$

$$\left.+\frac{p_2^2+\gamma_1 p_2+\gamma_2}{(p_2+a_3)(p_1-p_2)}\right]e^{p_2 t}\Big\} \equiv -\alpha_{t1}(1+a_1)\,\delta(t) - \mathfrak{m}_2(t),\quad p_{1,2} = b_2 \pm b_4,$$

$$B_{11} = -\alpha_{t1}a_4\frac{1+a_1}{1-a_1}\Big\{\delta(t) + \left[\frac{(\gamma_1-2b_2)\,p_1+\gamma_2-b_3}{p_1-p_2} -\right.$$

$$\left.-a_3\frac{p_1^2+\gamma_1 p_1+\gamma_2}{(p_1+a_3)(p_1-p_2)}\right]e^{p_1 t} - \left[\frac{(\gamma_1-2b_2)\,p_2+\gamma_2-b_3}{p_1-p_2} -\right.$$

$$\left.-a_3\frac{p_2^2+\gamma_1 p_2+\gamma_2}{(p_2+a_3)(p_1-p_2)}\right]e^{p_2 t} - a_3\frac{a_3^2-\gamma_1 a_3+\gamma_2}{(a_3+p_1)(a_3+p_2)}\,e^{-a_3 t}\Big\} \equiv$$

$$\equiv -\alpha_{t1}\frac{1+a_1}{1-a_1}\,\delta(t) + \mathfrak{m}_3(t),$$

$$B_{21} = 2\alpha_{t1}\frac{a_4}{1-a_1}\Big\{\delta(t) + \frac{(1-2b_2\theta_2)\,p_1-b_3\theta_2}{\theta_2(p_1-p_2)}\,e^{p_1 t} -$$

$$-\frac{(1-2b_2\theta_2)\,p_2-b_3\theta_2}{\theta_2(p_1-p_2)}\,e^{p_2 t}\Big\} \equiv 2\alpha_{t1}\frac{a_4}{1-a_1}\,\delta(t) + \mathfrak{m}_4(t),$$

$$E_1 = a_4[\delta(t) - a_3 e^{-a_3 t}],\quad E_2 = \frac{3E_{20}}{1-2\nu_{20}}\left[\delta(t) - \frac{2a_0}{\theta_2}\,e^{-\frac{1+2a_0}{\theta_2}t}\right],$$

$$b_1 = \frac{\alpha_{t1} a_4 (1+\nu_{20})}{\theta_2 E_{20} (1-a_1)}, \quad 2b_2 = \frac{a_3 - a_1 a_2}{1-a_1} + \frac{1}{\theta_2} + \frac{a_4 (1+\nu_{20})}{\theta_2 E_{20} (1-a_1)},$$

$$b_3 = \frac{a_3 - a_1 a_2}{(1-a_1)\theta_2}, \quad b_4^2 = b_2^2 - b_3 > 0, \quad \nu_1 = \frac{a_3 + a_1 a_2}{1+a_1} +$$

$$+ \frac{1}{\theta_2} - \frac{a_4 (1+\nu_{20})}{\theta_2 E_{20} (1+a_1)}, \quad \nu_2 = \frac{a_3 + a_1 a_2}{\theta_2 (1+a_1)},$$

$$1 + \nu_1 = (1+a_1)\delta(t) + a_1 (a_2 - a_3) e^{-a_3 t}, \quad 1 + \nu_2 = \frac{3a_0}{\theta_2} e^{-\frac{1+2a_0}{\theta_2} t}.$$

According to formulas (12), the thermoviscoelastic field in the Maxwell–Kelvin plate is described by the functions

$$u_1^v(r,t) = \frac{r}{R^2}\Big[-\alpha_{t1}(1+a_1)\int_0^R T_1(t,\rho)\rho d\rho -$$

$$- \int_0^t \int_0^R \mathfrak{m}_2(t-\tau) T_1(\tau,\rho)\rho d\rho d\tau\Big] + \alpha_{t1}\frac{1}{r}\Big[(1+a_1)\int_0^r T_1(t,\rho)\rho d\rho +$$

$$+ a_1(a_2 - a_3)\int_0^t \int_0^r e^{-a_3(t-\tau)} T_1(\tau,\rho)\rho d\rho d\tau\Big],$$

$$\sigma_{rr,1}^v(r,t) = -\alpha_{t1} a_4 \frac{1+a_1}{1-a_1}\frac{1}{R^2}\int_0^R T_1(t,\rho)\rho d\rho -$$

$$- \alpha_{t1} a_4 \frac{1}{r^2}\int_0^r T_1(t,\rho)\rho d\rho + \frac{1}{R^2}\int_0^t \int_0^R \mathfrak{m}_3(t-\tau) T_1(\tau,\rho)\rho d\rho d\tau +$$

$$+ \alpha_{t1} a_3 a_4 \int_0^t \int_0^r \frac{1}{r^2} e^{-a_3(t-\tau)} T_1(\tau,\rho)\rho d\rho d\tau,$$

$$\sigma_{\varphi\varphi,1}^v(r,t) = -\alpha_{t1} a_4 \frac{1+a_1}{1-a_1}\frac{1}{R^2}\int_0^R T_1(t,\rho)\rho d\rho +$$

$$+ \alpha_{t1} a_4 \frac{1}{r^2}\int_0^r T_1(t,\rho)\rho d\rho - \alpha_{t1} a_4 T_1(t,r) + \tag{16}$$

$$+ \frac{1}{R^2}\int_0^t \int_0^R \mathfrak{m}_3(t-\tau) T_1(\tau,\rho)\rho d\rho - \alpha_{t1} a_3 a_4 \frac{1}{r^2} \times$$

$$\times \int_0^t \int_0^r e^{-a_3(t-\tau)} T_1(\tau,\rho)\rho d\rho d\tau + \alpha_{t1} a_3 \int_0^t e^{-a_3(t-\tau)} T_1(\tau,r) d\tau,$$

$$u_2^v(r,t) = 2\frac{b_1}{b_4}\frac{1}{r}\int_0^t \int_0^R e^{-b_2(t-\tau)} \operatorname{sh} b_4(t-\tau) T_1(\tau,\rho)\rho d\rho d\tau +$$

$$+ \alpha_{t2}\frac{3a_0}{\theta_2 r}\int_0^r \int_R^t e^{-\frac{1+2a_0}{\theta_2}(t-\tau)} T_2(\tau,\rho)\rho d\rho d\tau,$$

$$\sigma_{rr,2}^v(r,t) = -2\alpha_{t1}\frac{a_4}{1-a_1}\frac{1}{r^2}\int_0^R T_1(t,\rho)\rho d\rho -$$

$$- \alpha_{t2}\frac{3E_{20}}{1-2\nu_{20}}\frac{1}{r^2}\int_R^r T_2(\tau,\rho)\rho d\rho - \frac{1}{r^2}\int_0^t \int_0^R \mathfrak{m}_4(t-\tau) T_1(\tau,\rho)\rho d\rho d\tau +$$

$$+ \alpha_{t2}\frac{6a_0 E_{20}}{\theta_2(1-2\nu_{20})}\frac{1}{r^2}\int_0^t \int_R^r e^{-\frac{1+2a_0}{\theta_2}} T_2(\tau,\rho)\rho d\rho d\tau,$$

$$\sigma^{v}_{\varphi\varphi,2}(r,\ t) = 2\alpha_{t1}\frac{a_4}{1-a_1}\frac{1}{r^2}\int_0^R T_1(t,\ \rho)\rho d\rho +$$

$$+\frac{3\alpha_{t2}E_{20}}{1-2\nu_{20}}\frac{1}{r^2}\int_R^r T_2(\tau,\ \rho)\rho d\rho + \frac{1}{r^2}\int_0^t\int_0^R \mathfrak{m}_4(t-\tau)T_1(\tau,\ \rho)\rho d\rho d\tau -$$

$$-\frac{6a_0\alpha_{t2}E_{20}}{\theta_2(1-2\nu_{20})r^2}\int_0^t\int_R^r e^{-\frac{1+2a_0}{\theta_2}(t-\tau)}T_2(\tau,\ \rho)\rho d\rho d\tau -$$

$$-\alpha_{t2}\frac{3E_{20}}{1-2\nu_{20}}\left[T_2(t,\ r)-\frac{2a_0}{\theta_2}\int_0^t e^{-\frac{1+2a_0}{\theta_2}(t-\tau)}T_2(\tau,\ r)\,d\tau\right].$$

The deductions from formulas (16) are the same as the deductions for the Biot-Maxwell plate (we replace Biot-Maxwell by Maxwell-Kelvin).

Repeating the above considerations, we can easily obtain formulas for calculating the thermoviscoelastic state of Maxwell-Biot, Kelvin-Biot, and Kelvin-Maxwell models.

NOTATION

λ_j, thermal conductivity; a_j^2, thermal diffusivity; r_{12}, coefficient of heat resistance; ε^{-1}, time of relaxation; θ, time lag; G_{10}, shear modulus of the Maxwell plate; ν_{10}, Poisson ratio of the Maxwell plate; ν_{20}, Poisson ratio of the Kelvin plate; E_{20}, modulus of elasticity of the Kelvin plate.

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