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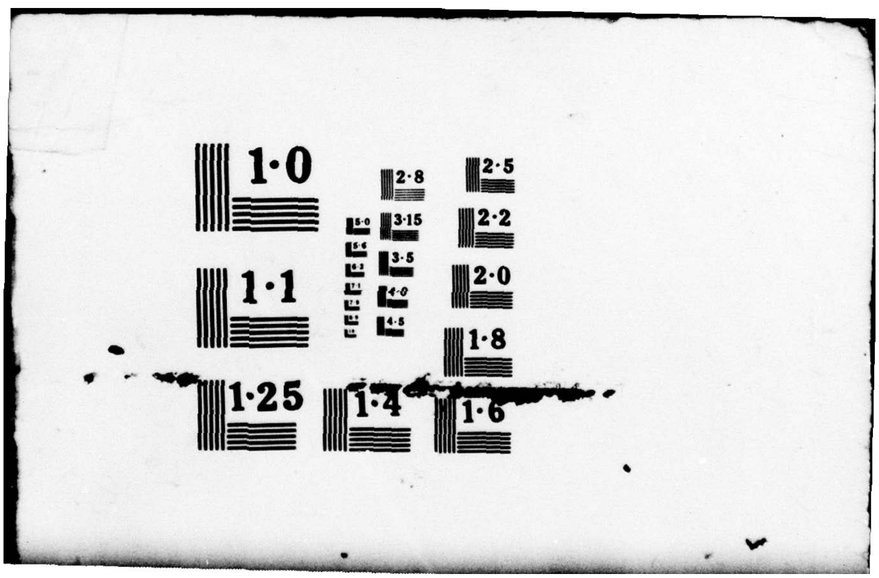
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SOLUTION OF THE THERMOELASTICITY PROBLEMS FOR A WEDGE BY MEANS OF THE INTEGRAL MELLIN TRANSFORM

By

V. M. Khorol'skiy

FOREIGN TECHNOLOGY DIVISION

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EDITED TRANSLATION

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$sinh^{-1}$
cos	cos	ch	cosh	arc ch	$cosh^{-1}$
tg	tan	th	tanh	arc th	$tanh^{-1}$
ctg	cot	cth	coth	arc cth	$coth^{-1}$
sec	sec	sch	sech	arc sch	$sech^{-1}$
cosec	csc	csch	csch	arc csch	$csch^{-1}$

Russian	English
rot	curl
lg	log

SOLUTION OF THE THERMOELASTICITY PROBLEMS FOR A WEDGE BY MEANS OF THE INTEGRAL MELLIN TRANSFORM

V. M. Khorol'skiy

Let us assume that the temperature field in the wedge is known and has the form

$$T=T(\varphi, r, t); \quad 0\leqslant r<\infty; \quad -\psi\leqslant\varphi\leqslant\psi,$$

where 2ψ - angle of opening of the wedge;

(r, ϕ) - polar coordinates of the point.

The thermal stresses and shifts we seek in the form of the sum [3]

$$\sigma_\varphi=\bar{\sigma}_\varphi+\bar{\bar{\sigma}}_\varphi; \quad \sigma_r=\bar{\sigma}_r+\bar{\bar{\sigma}}_r; \quad \tau_{r\varphi}=\bar{\tau}_{r\varphi}+\bar{\bar{\tau}}_{r\varphi}; \quad u=\bar{u}+\bar{\bar{u}}; \quad v=\bar{v}+\bar{\bar{v}}.$$

Stresses and shifts, marked by one line, are determined by the thermoelastic potential of shifts Θ, which is determined from the equation

$$\Delta\Theta=\delta T; \quad \Delta=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}. \qquad (1)$$

Here μ, α_t, and G - Poisson coefficient, coefficient of linear expansion, and shear modulus; for the case of the plane stressed and deformed state the coefficient δ is equal to $(1+\mu)\alpha_t$ and $\frac{1+\mu}{1-\mu}\alpha_t$, respectively; u and v are shifts along the axes r and ϕ.

It is known that the temperature field, which satisfies the heat-conductivity equation $a\Delta T=\frac{\partial T}{\partial t}$, is analytical with respect to the coordinates [4]; consequently, this field can always be presented in the form

$$T = \frac{1}{2\pi i}\int_z h(\varphi, \lambda, t) r^{-\lambda} d\lambda; \quad h(\varphi, \lambda, t) = \int_0^\infty T(\varphi, r, t) r^{\lambda-1} dr,$$

where a - heat-conductivity coefficient;

$\lambda = k + i\omega$ - complex variable;

z - a certain straight line which is parallel to an imaginary axis; $k_1 < k < k_2$; the numbers k_1 and k_2 are selected on the basis of the behavior of the temperature field at 0, ∞.

The thermoelastic potential of shifts we seek in the form

$$\Theta = \frac{1}{2\pi i}\int_z f(\varphi, \lambda + 2, t) r^{-\lambda} d\lambda.$$

Proceeding from relationship (1) we obtain a differential equation for determining the unknown function $f(\phi, \lambda, t)$,

$$f(\varphi, \lambda, t)(2-\lambda)^2 + f''_\varphi(\varphi, \lambda, t) = \delta h(\varphi, \lambda, t). \quad (2)$$

Stresses and shifts from the thermoelastic potential of shifts are written as [3]

$$\bar{\sigma}_r + \bar{\sigma}_\varphi = -2G\Delta T = -\frac{G\delta}{\pi i}\int_z h(\varphi, \lambda, t) r^{-\lambda} d\lambda,$$

$$\bar{\sigma}_\varphi + i\bar{\tau}_{r\varphi} = -2G(\bar{u}_r' - i\bar{v}_r'); \quad (3)$$

$$\bar{\sigma} + i\bar{\tau}_{r\varphi} = -\frac{G\delta}{\pi i}\int_z [f(\varphi, \lambda, t)(2-\lambda) - if_\varphi'(\varphi, \lambda, t)](1-\lambda) r^{-\lambda} d\lambda; \quad (4)$$

$$\bar{\sigma}_\varphi - \bar{\sigma}_r = \frac{G\delta}{\pi i}\int_z [f(\varphi, \lambda, t)(2-\lambda)\lambda + f_\varphi''(\varphi, \lambda, t)] r^{-\lambda} d\lambda. \quad (5)$$

If the sides of the wedge are free of loads, the boundary conditions for stresses marked by double lines are written as

$$(\bar{\bar{\sigma}}_\varphi + i\bar{\bar{\tau}}_{r\varphi})_{\varphi=\psi_j} = \frac{G\delta}{\pi i}\int_z [f(\psi_j, \lambda, t)(2-\lambda) - if_\varphi'(\psi_j, \lambda, t)](1-\lambda) r^{-\lambda} d\lambda, \quad (6)$$

where

$$j = 1, 2; \quad \psi_1 = \psi; \quad \psi_2 = -\psi.$$

If the sides of the wedge are rigidly secured, the boundary conditions for shifts, after differentiating for r, have the form

$$-2G(\bar{\bar{u}}_r' - i\bar{\bar{v}}_r')_{\varphi=\psi_j} = (\bar{\sigma}_\varphi + i\bar{\tau}_{r\varphi})_{\varphi=\psi_j}. \quad (7)$$

The boundary conditions are written with the same simplicity if one side of the wedge is free and the other is secured.

It is characteristic that the indicated thermoelastic problems are reduced to the basic problems of the elasticity theory with boundary conditions which are presented in the form of the Mellin's integrals. Let's examine individually the basic problems of the elasticity theory for a wedge and present their general solution.

Let's assume that surface stresses, assigned in the form of Mellin's integrals, are distributed on the sides of a wedge

$$(\sigma_\varphi + i\tau_{r\varphi})_{\varphi=\varphi_j} = \frac{1}{2\pi i}\int_L a_j(\lambda) r^{-\lambda} d\lambda.$$

Stresses and shifts we will seek in the form of complex Kolosov-Muskhelishvili potentials [2]

$$(\sigma_\varphi + i\tau_{r\varphi} = \Phi(z) + \overline{\Phi(z)} + e^{2i\varphi}[\bar{z}\Phi'(z) + \psi(z)],$$

$$\sigma_\varphi - \sigma_r + 2i\tau_{r\varphi} = 2e^{2i\varphi}[\bar{z}\Phi'(z) + \psi(z)],$$

$$-2G(u'_r - iv'_r) = [-\varkappa\overline{\Phi(z)} + \Phi(z)] + e^{2i\varphi}[\bar{z}\Phi'(z) + \psi(z)].$$

The unknown analytical functions in the wedge we seek in the form

$$\Phi(z) = \frac{1}{2\pi i}\int_L a(\lambda) z^{-\lambda} d\lambda; \quad \Psi(z) = \frac{1}{2\pi i}\int_L b(\lambda) z^{-\lambda} d\lambda.$$

Taking the boundary conditions into account, we obtain a system of equations for determining the unknown functions of the complex variable $a(\lambda)$, $b(\lambda)$, the solution of which has the form

$$a(\lambda) = \frac{1}{\Delta_1(\lambda)\Delta_2(\lambda)}[D_1(\lambda)(1-\lambda)\sin 2\psi - \bar{D_1}(\lambda)\sin 2(1-\lambda)\psi];$$

$$b(\lambda) = D_2(\lambda) - a(\lambda)(1-\lambda)\cos 2\psi - \bar{a}(\lambda)\cos 2(1-\lambda)\psi,$$

where

$$\Delta_{1,2}(\lambda) = (1-\lambda)\sin 2\psi \pm \sin 2(1-\lambda)\psi; \ \bar{D}_1(\lambda) = \overline{D_1(\bar{\lambda})};$$

$$D_1(\lambda) = -\frac{1}{2i}\left[a_1(\lambda)e^{i(\lambda-2)\psi} - a_2(\lambda)e^{-i(\lambda-2)\psi}\right];$$

$$D_2(\lambda) = \frac{1}{2}\left[a_1(\lambda)e^{i(\lambda-2)\psi} + a_2(\lambda)e^{-i(\lambda-2)\psi}\right].$$

In particular, for a symmetrical normal load

$$\sigma_\varphi|_{\varphi=\pm\psi} = \frac{1}{2\pi i}\int_L a(\lambda) r^{-\lambda} d\lambda; \quad \tau_{r\varphi}|_{\varphi=\pm\psi} = 0$$

we have

$$a(\lambda) = \frac{a(\lambda)}{\Delta_1(\lambda)}\sin(2-\lambda)\psi; \quad b(\lambda) = -\frac{a(\lambda)}{\Delta_1(\lambda)}\lambda\sin\lambda\psi.$$

For the second basic problem of the elasticity theory, when the shifts on the sides of the wedge have the form

$$-2G(u'_r - iv'_r)_{\varphi=\psi} = \frac{1}{2\pi i}\int_L a_r(\lambda) r^{-\lambda} d\lambda,$$

we obtain

$$a(\lambda) = \frac{1}{\Delta_1(\lambda)\Delta_2(\lambda)}[D_1(\lambda)(1-\lambda)\sin 2\psi + \varkappa\bar{D}_1(\lambda)\sin 2(1-\lambda)\psi];$$

$$b(\lambda) = D_2(\lambda) + \varkappa\bar{a}(\lambda)\cos 2(1-\lambda)\psi - a(\lambda)(1-\lambda)\cos 2\psi;$$

$$\Delta_{1,2}(\lambda) = (1-\lambda)\sin 2\psi \pm \varkappa\sin 2(1-\lambda)\psi.$$

The obtained solutions of the basic problems of the elasticity theory for a wedge represent an independent interest due to their generality and compactness. From general solutions it is easy to obtain calculation formulas for the various particular cases, which is convenient in the problems of thermoelasticity. The solutions, available in the literature, of the basic problems of elasticity for a wedge are based on the Papkovich-Neyber concepts and have a more complex form [6].

Let us examine an important particular case where the temperature field in the wedge has the form

$$T = \frac{\xi(\alpha\varphi)}{2\pi i}\int_L g(\lambda, t) r^{-\lambda} d\lambda; \qquad \xi(\alpha\varphi) = A\,\mathrm{ch}\,\alpha\varphi + B\,\mathrm{sh}\,\alpha\varphi.$$

Assuming that in the equation [2] we have

$$f(\varphi, \lambda, t) = \xi(\alpha\varphi) p(\lambda, t); \; h(\varphi, \lambda, t) = \xi(\alpha\varphi) g(\lambda, t),$$

we obtain

$$p(\lambda, t) = \frac{\delta g(\lambda, t)}{(2-\lambda)^2 + \alpha^2}.$$

Stresses from the thermoelastic potential of shifts and the boundary conditions will be written by the formulas (3)-(7), if we assume that

$$f(\varphi, \lambda, t) = \frac{\delta\xi(\alpha\varphi) g(\lambda t)}{(2-\lambda)^2 + \alpha^2}.$$

Assuming that in the preceding formulas $\xi(\alpha\varphi) \equiv 1$ we obtain a case of an axisymmetric temperature field

$$T(r, t) = \frac{1}{2\pi i}\int_L g(\lambda, t) r^{-\lambda} d(\lambda).$$

Let us wtite the formulas for temperature streses. The boundary conditions for complex potentials for the free sides are written as

$$\bar{\bar{\sigma}}_{\varphi/\varphi=\pm\psi} = \frac{G\delta}{\pi i}\int_L \frac{1-\lambda}{2-\lambda} g(\lambda, t) r^{-\lambda} d\lambda; \; \bar{\bar{\tau}}_{r\varphi/\varphi=\pm\varphi} = 0.$$

Adding the stresses and shifts with one and two lines, we have

$$\sigma_r+\sigma_\varphi=\frac{G\delta}{\pi i}\int_z\left[\frac{4(1-\lambda)}{(2-\lambda)\Delta_1(\lambda)}\sin(2-\lambda)\psi\cos\lambda\varphi-1\right]g(\lambda,t)r^{-\lambda}d\lambda;$$

$$\sigma_\varphi-\sigma_r=\frac{G\delta}{\pi i}\int_z\frac{(-\lambda)}{2-\lambda}\left\{\frac{2(1-\lambda)}{\Delta_1(\lambda)}[\cos\lambda\varphi\sin(2-\lambda)\psi+\right.$$

$$\left.+\sin\lambda\psi\cos(\lambda-2)\varphi]-1\right\}g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$\tau_{r\varphi}=\frac{G\delta}{\pi i}\int_z\frac{\lambda(1-\lambda)}{(2-\lambda)\Delta_1(\lambda)}[\sin\lambda\varphi\sin(2-\lambda)\psi-$$

$$-\sin\lambda\psi\sin(2-\lambda)\varphi]g(\lambda,t)\,r^{-\lambda}\,d\lambda;$$

$$-u'_r=\frac{\delta}{2\pi i}\int_z\frac{1-\lambda}{2-\lambda}\left\{\frac{1}{\Delta_1(\lambda)}[(1-\varkappa-\lambda)\cos\lambda\varphi\sin(2-\lambda)\psi-\right.$$

$$\left.-\lambda\sin\lambda\psi\cos(\lambda-2)\varphi]-1\right\}g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$v'_r=\frac{\delta}{2\pi i}\int_z\frac{1-\lambda}{(2-\lambda)\Delta_1(\lambda)}[\lambda\sin\lambda\psi\sin(2-\lambda)\varphi-$$

$$-(1+\varkappa-\lambda)\sin\lambda\varphi\sin(2-\lambda)\psi]g(\lambda,t)\,r^{-\lambda}d\lambda.$$

In the case of a rigid fixing of the sides the boundary conditions are written as

$$-2G\overline{\overline{u}}'_r/_{\varphi=\pm\psi}=\frac{G\delta}{\pi i}\int_z\frac{1-\lambda}{2-\lambda}g(\lambda,t)\,r^{-\lambda}d\lambda;\quad \overline{\overline{v}}'_r/_{\varphi=\pm\psi}=0.$$

The calculation formulas have the form

$$\sigma_\varphi+\sigma_r=\frac{G\delta}{\pi i}\int_z\left[\frac{4(1-\lambda)}{(2-\lambda)\Delta_2(\lambda)}\sin(2-\lambda)\psi\cos\lambda\varphi-1\right]g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$\sigma_\varphi-\sigma_r=\frac{G\delta}{\pi i}\int_z\frac{1}{2-\lambda}\left\{\frac{2(1-\lambda)}{\Delta_2(\lambda)}[(-\lambda)\sin(2-\lambda)\psi\cos\lambda\varphi+\right.$$

$$\left.+(1+\varkappa-\lambda)\sin\lambda\psi\cos(\lambda-2)\varphi]+\lambda\right\}g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$\tau_{r\varphi}=\frac{G\delta}{\pi i}\int_z\frac{1-\lambda}{(2-\lambda)\Delta_2(\lambda)}[\lambda\sin(2-\lambda)\psi\sin\lambda\varphi+$$

$$+(1+\varkappa-\lambda)\sin\lambda\psi\sin(2-\lambda)\varphi]g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$-u'_r=\frac{\delta}{2\pi i}\int_z\frac{1-\lambda}{2-\lambda}\left\{\frac{1}{\Delta_2(\lambda)}[(1-\varkappa-\lambda)\cos\lambda\varphi\sin(2-\lambda)\psi+\right.$$

$$\left.+(1+\varkappa-\lambda)\sin\lambda\psi\sin(2-\lambda)\varphi]-1\right\}g(\lambda,t)\,r^{-\lambda}d\lambda;$$

$$v'_r=\frac{\delta}{2\pi i}\int_z\frac{(1-\lambda)(1+\varkappa-\lambda)}{(2-\lambda)\Delta_2(\lambda)}[\sin(\lambda-2)\psi\sin\lambda\varphi+$$

$$+\sin(2-\lambda)\varphi\sin\lambda\psi]g(\lambda,t)r^{-\lambda}d\lambda.$$

Thus, the problem of determining the temperature stresses for an axisymmetrical temperature field is reduced to the calculation of the function

$$g(\lambda,t)=\int_0^\infty T(r,t)r^{\lambda-1}dr.$$

As an example, let's examine the case where a heat source with intensity **q** acts at the apex of the wedge for the period of time t. If the initial temperature is equal to zero and the sides of the wedge are heat insulated, the temperature field has the form [3]

$$T = -\frac{q}{4\psi\lambda_t} Ei(-\rho^2),$$

where λ_t - heat-conductivity coefficient;

$Ei(-r)$ - integral power function;

$\rho^2 = r^2/4at$ - value which is inverse to the Fourier criterion.

The function $g(\lambda, t)$ in this case has the form [1]

$$g(\lambda, t) = \frac{A_0}{\lambda} \Gamma\left(\frac{\lambda}{2}\right); \; \Gamma(\lambda) \text{ - gamma function, } A_t = \frac{q}{4\psi\lambda_t}.$$

Taking into account the singular points of the gamma function and using the theory of deductions, we obtain the calculation formulas for thermal stresses in series. Thus, for example, for the case of free sides the stresses and shifts will be written as

$$\gamma_n = \sin 2\psi + \frac{\sin 2(2n+1)\psi}{2n-1}; \; A = \frac{qG\delta}{4\psi\lambda_t}; \; B = \frac{q\delta}{4\psi\lambda_t};$$

$$\sigma_r + \sigma_\varphi = -2A\sum_{n=1}^{\infty} \frac{(-1)^n \rho^{2n}}{n!n} \left\{1 - \frac{2\sin(2n+2)\psi\cos 2n\psi}{(n+1)\gamma_n}\right\}; \tag{8}$$

$$\sigma_r - \sigma_\varphi = 4A\sum_{n=1}^{\infty} \frac{(-1)^n \rho^{2n}}{(n+1)!} \left\{\frac{1}{2} + \frac{\cos(2n+2)\varphi\sin 2n\psi - \sin(2n+2)\psi\cos 2n\varphi}{\gamma_n}\right\}; \tag{9}$$

$$\tau_{r\varphi} = 2A\sum_{n=1}^{\infty} \frac{(-1)^n \rho^{2n}}{(n+1)!\gamma_n} \left\{\sin(2n+2)\psi\sin 2n\varphi - \sin(2n+2)\varphi\sin 2n\psi\right\}; \tag{10}$$

$$u_r' = \frac{B}{2}\sum_{n=1}^{\infty} \frac{(-1)^n \rho^{2n}}{(n+1)!n} \left\{\frac{(1-\varkappa+2n)\cos 2n\varphi\sin(2+2n)\psi - 2n\sin 2n\psi\cos(2+2n)\varphi}{\gamma_n} - \frac{1}{1+2n}\right\};$$

$$-v_r' = \frac{B}{2}\sum_{n=1}^{\infty} \frac{(-1)^n \rho^{2n}}{(n+1)!n\gamma_n} \left\{(1+\varkappa+2n)\sin 2n\varphi\sin(2+2n)\psi + 2n\sin 2n\psi\sin(2+2n)\varphi\right\}.$$

We note that the series which correspond to the roots of the denominator $\Delta_{1,2}(\lambda) = 0$, represent homogeneous solutions [5], i. e., do not cause stresses on the sides of the wedge and, therefore, can be omitted.

The formulas for the stresses, (8)-(10), coincide with the solution obtained by the method of power series in work [7].

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