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Application of the Theorem of Deductions in the Solution of Some Mechanical Tasks

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Annotation: *In article on model of filtration of liquid in the jointed and porous environment the regional task is considered. Boundary conditions turn out through "sewing together" of boundary sizes on a joint of layer and the well. It is solved by meth-od, based on the theory of deduction. Here advantage of this method as additions is shown to Fourier's method in his weak point, in decomposition of this function on own functions for satisfaction of entry conditions.*

Keywords: *reservoir pressure, estuarial pressure, jointed and porous layer, liquid filtration, boundary condition of the third sort, characteristic equation, theory of deduction, Fourier's method.*

Introduction. Reservoir pressure is important characteristic of a condition of a bedded system. Therefore it is necessary to exercise control over change in time of this size. However change of reservoir pressure sometimes demands a long stop of the well, day and even dozens of days. Definition bottomhole and bedded pressure in wells is connected with carrying out the special researches demanding time of a long time and a stop of the well. Therefore it is important to be able to determine these sizes on the basis of data on operation of the well determined on the mouth. In use delivery or operational wells, it is often necessary to know bottomhole pressure. Determination of this size by means of the bottomhole manometer is technologically inconvenient. Therefore it is important to be able to count bottomhole pressure on the mouth. In case of delivery or operational wells with a big output and low content of gas (i.e. in cases when losses on friction are notable) bottomhole pressure can be counted rather precisely.

Method. Let's consider a task of collaboration of layer and the well, concluded in change of boundary conditions. Layer is accepted non-uniform, jointed and porous. Filtration of poorly compressed liquid in the jointed and porous environment in the assumption that filtration of liquid comes on cracks taking into account an overflow from blocks/1/, is described by the following equation:

$$\frac{\partial p}{\partial t} = \aleph \frac{\partial^2 p}{\partial x^2} + h\frac{\partial^3 p}{\partial t \partial x^2} \qquad (1)$$

Usually in practice pressure defining the mode of selection of liquid from layer is set on the mouth (gallery). Inflow of liquid from layer to gallery is defined as

$$Q_1 = -S_1 \frac{k}{\mu} \cdot \left.\frac{\partial p}{\partial x}\right|_{x=0},$$

where S_1 - area of filtration, k - permeability coefficient, μ - viscosity coefficient. Let on the mouth to gallery constant pressure be set p_0. In the subcritical modes for a stationary current the liquid consumption in the well can be presented a formula

$$Q_2 = \varepsilon \cdot \left(p\big|_{x=0} - p_0 \right).$$

where ε - constant. From equality of expenses Q_1 and Q_2 let's receive a boundary condition of the third sort on p, the considering influence of gallery:

$$p(t,0) + \frac{k \cdot S_1}{\varepsilon \cdot \mu} \cdot \frac{\partial p(t,0)}{\partial x} = p_0. \qquad (2)$$

The second boundary condition:

$$p(t,L) = p_1. \qquad (3)$$

Entry condition:

$$p(0,x) = \varphi_o(x). \qquad (4)$$

In such problem statement (1) - (4) considers inflow of liquid to gallery from layer with the set pressure on the mouth (gallery). We pass to dimensionless variables

$$\mathcal{R} = \frac{p}{p_1}, \quad X = \frac{x}{\sqrt{\aleph t_0}}, \quad \tau = \frac{t}{t_0}.$$

Then we will receive

$$\frac{p_1}{t_0} \cdot \frac{\partial \mathcal{R}}{\partial \tau} = \aleph \frac{\partial^2 \mathcal{R}}{\partial x^2} \cdot \frac{p_1}{\aleph t_0} + \eta \frac{\partial^3 \mathcal{R}}{\partial \tau \partial x^2} \cdot \frac{p_1}{t_0^2 \aleph}.$$

Let's increase both parts on $\frac{t_0}{p_1}$:

$$\frac{\partial \mathcal{R}}{\partial \tau} = \frac{\partial^2 \mathcal{R}}{\partial x^2} + \eta_1 \frac{\partial^3 \mathcal{R}}{\partial \tau \partial x^2}, \qquad (5)$$

where $\eta_1 = \frac{\eta}{\aleph t_0}$.

Boundary and entry conditions

$$\mathcal{R}(t,0) + \frac{k \cdot S_1}{\varepsilon \mu \sqrt{\aleph t_0}} \cdot \frac{\partial \mathcal{R}(t,0)}{\partial x} = p_{01}, \qquad (6)$$

$$\mathcal{R}(t,1) = 1, \qquad (7)$$

$$\mathcal{R}(0,x) = \varphi_{01}(x), \qquad (8)$$

where $p_{01}=\dfrac{p_0}{p_1},\ \ \varphi_{01}(x)=\dfrac{\varphi_0(x)}{p_1}.$

We solve a problem (5) - (8) method of Cauchy. Cauchy's method demands zero boundary conditions/2/. Let's present function $R(x,t)$ as follows:

$$\mathcal{R}(x,t)=\mathcal{U}(x,t)+\mathcal{V}(x,t)+p_{01}. \qquad (9)$$

Then, if $\mathcal{U}(x,t)=\dfrac{1-p_{01}}{\beta-1}\cdot(\beta-x). \qquad (10)$

where $\beta=\dfrac{k\mathcal{S}_1}{\varepsilon\mu\sqrt{\aleph t_0}}$, that the initial task (5) - (8) will correspond concerning function $\mathcal{V}(x,t)$ as follows

$$\frac{\partial\mathcal{V}}{\partial t}=\frac{\partial^2\mathcal{V}}{\partial x^2}+\eta_1\frac{\partial^3\mathcal{V}}{\partial\tau\partial x^2}, \qquad (11)$$

$$\mathcal{V}(0,\tau)+\beta\cdot\mathcal{V}_x(0,\tau)=0,\ \ \mathcal{V}(1,\tau)=0, \qquad (12)$$

$$\mathcal{V}(x,0)=f_0(x), \qquad (13)$$

where $f_0(x)=\varphi_{01}-p_{01}-\dfrac{1-p_{01}}{\beta-1}\cdot(\beta-x).$

In Cauchy's method, as well as in Fourier's method, the decision is looked for in a look

$$\mathcal{V}(x,t)=\sum_{-\infty}^{+\infty}\mathcal{X}(x)\cdot\mathcal{T}(\tau). \qquad (14)$$

Then for function definition $\mathcal{X}(x)$ and $\mathcal{T}(\tau)$ we have to the equation:

$$\begin{cases}\mathcal{X}(x)\cdot\mathcal{T}(\tau)=\mathcal{X}''(x)\cdot\mathcal{T}(\tau)+\eta_1\mathcal{X}''\cdot\mathcal{T}',\\ \dfrac{\mathcal{T}'(\tau)}{\mathcal{T}(\tau)+\eta_1\mathcal{T}'(\tau)}=\dfrac{\mathcal{X}''(x)}{\mathcal{X}}=\alpha,\end{cases} \qquad (15)$$

where α- any constant.

For (15) corresponds the characteristic equations:

$$\begin{cases}\dfrac{\omega}{1+\eta_1\omega}=\alpha, & (16)\\ \lambda^2=\alpha, & (17)\end{cases}$$

since α- any constant, in the equation (17) one root can be chosen randomly $\lambda_1=\theta$ and the second root λ_2 to express through the first. In that specific case for (17), $\lambda_2=-\theta$.

Then function $\mathscr{X}(x)$ will be defined as

$$\mathscr{X}(x) = A \cdot e^{\theta x} + B \cdot e^{-\theta x}.$$

Meeting boundary conditions (12) we have for constant *A and B*:

$$\begin{cases} A \cdot (1 + \beta\theta) - B \cdot (1 - \beta\theta) = 0, \\ A \cdot e^{\theta} + B \cdot e^{\theta} = 0. \end{cases}$$

The system has the decision other than zero when the determinant is equal to zero, i.e.

$$\mathfrak{D}(\theta) = (1 + \beta\theta) \cdot e^{-\theta} - (1 - \beta\theta) \cdot e^{\theta} = 0. \quad (18)$$

Then *A* and *B* can be taken

$$A = (\beta\theta - 1) \cdot C,$$
$$B = (\beta\theta + 1) \cdot C,$$

where for convenience: *C* =.

From there is a function $\mathscr{X}(x)$ will be defined as

$$\mathscr{X}(x) = (\beta\theta - 1) \cdot e^{\theta x} + (\beta\theta + 1) \cdot e^{-\theta x}. \quad (19)$$

From the characteristic equation (16), replacing α on θ^2, we make function

$$\Phi(\theta, \omega) = \omega \cdot (1 - \theta^2 \eta_1) - \theta^2, \quad (20)$$

by means of which the solution of a task (11) registers, (12):

$$\mathcal{V}(x, \tau) = E_{\theta} E_{\omega} \left[\frac{\varphi(\theta, \omega) \cdot e^{\omega\tau}}{\Phi(\theta, \omega)} \cdot \frac{\mathscr{X}(x)}{\mathfrak{D}(\theta)} \right],$$

where through E_{ω} deduction on a variable is designated ω, through E_{θ} - deduction on a variable θ, $\varphi(\theta, \omega)$- any function which is chosen so that to meet an entry condition (12).

Following the Koshe procedure, we choose function $\varphi(\theta, \omega)$ in the following look

$$\varphi(\theta, \omega) = (\theta + h) \cdot \int_0^1 \frac{\Phi(\theta, \omega) - \Phi(\theta, f)}{\omega - f} \cdot e^{\theta(1-q)} dq.$$

And, after performance of division under a sign of integration, in the received expression $f^0(q)$ we replace with initial function $f_0(q)$.

Performing this procedure taking into account (18), we will receive:

$$\varphi(\theta, \omega) = (\theta + h) \int_0^1 (1 - \theta^2 \eta) \cdot f_0(q) e^{\theta(1-q)} dq,$$

then

$$\mho(x,\tau)=\mathop{E}_{\theta}\frac{(1-\beta\theta)e^{\theta x}-(1+\beta\theta)e^{-\theta x}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot\int_0^1(1-\theta^2\eta)e^{\theta(1-q)}\cdot f_0(q)dq\times$$
$$\times\mathop{E}_{\omega}\frac{e^{\omega\tau}}{\omega(1-\theta^2\eta)-\theta^2}. \tag{21}$$

Let's show that $\mho(x,\tau)$, defined (21) taking into account (13) meets an entry condition. To the place $\mathscr{X}(x)$ and $\mathfrak{D}(\theta)$ let's substitute their values from (18) and (19):

$$\mho(x,0)=\mathop{E}_{\theta}\frac{(\beta\theta-1)e^{\theta x}+(\beta\theta+1)e^{-\theta x}}{(1+\beta\theta)e^{-\theta}-(1-\beta\theta)e^{\theta}}\cdot(\theta+h)\int_0^1 e^{\theta(1-q)}f_0(q)dq=$$

$$=\mathop{E}_{\theta}\frac{(\beta\theta-1)e^{\theta x}+(\beta\theta+1)e^{-\theta x}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot(\theta+h)\int_0^1 e^{\theta(1-q)}f_0(q)dq=$$

$$=\mathop{E}_{\theta}\frac{(\beta\theta-1)e^{\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot(\theta+h)\int_0^1 e^{-\theta(q-x)}f_0(q)dq+$$

$$+\mathop{E}_{\theta}\frac{(\beta\theta+1)e^{\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot(\theta+h)\int_0^1 e^{-\theta(q+x)}f_0(q)dq. \tag{22}$$

Here the first member is equal $f_0(x)$, that to us it is also necessary. And the second member at anything $x>0$ it is equal to zero.

On a basic formula of Cauchy

$$\lim_{z\to\infty}\frac{1}{2\pi i}\cdot\int\frac{\psi(z)}{\gamma(z)}\cdot f(z,q)dz=\sum_{n=1}^{\infty}\frac{\psi(\lambda_n)}{\gamma'(\lambda_n)}\cdot f(\lambda_n,q).$$

If $\gamma(z)=\psi(z)+\chi(z)$,

$$\lim_{z\to\infty}\frac{\chi(z)}{\gamma(z)}=1,\qquad \lim_{z\to\infty}\frac{\chi(-z)}{\gamma(-z)}=0,$$

$$\lim_{z\to\infty}\frac{\psi(z)}{\gamma(z)}=0,\qquad \lim_{z\to\infty}\frac{\psi(-z)}{\gamma(-z)}=1,$$

$$\lim_{z\to\infty}\frac{\psi(z)}{\gamma(z)}e^{z(q-q_0)}=0,\qquad \lim_{z\to\infty}\frac{\chi(-z)}{\gamma(-z)}e^{z(q_1-q)}=0.$$

Let's designate $\gamma(\theta)=(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}$,

$$\chi(\theta) = (1-\beta\theta)e^{\theta},$$

$$\psi(\theta) = -(1+\beta\theta)e^{-\theta}.$$

We check conditions of limits

$$\lim_{\theta\to+\infty}\frac{\chi(\theta)}{\gamma(\theta)} = \lim_{\theta\to+\infty}\frac{(1-\beta\theta)e^{\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}} = 1,$$

$$\lim_{\theta\to+\infty}\frac{\psi(\theta)}{\gamma(\theta)} = -\lim_{\theta\to+\infty}\frac{(1+\beta\theta)e^{-\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}} = 0,$$

$$\lim_{\theta\to+\infty}\frac{\psi(\theta)}{\gamma(\theta)}\cdot e^{\theta(q-q_0)} = -\lim_{\theta\to+\infty}\frac{(1+\beta\theta)e^{\theta(q-q_0-2)}}{(1-\beta\theta)-(1+\beta\theta)e^{-2\theta}} = 0,$$

$$q < q_0 + 2,$$

$$\lim_{\theta\to-\infty}\frac{\chi(\theta)}{\gamma(\theta)} = \lim_{\theta\to-\infty}\frac{(1-\beta\theta)e^{\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}} = 0,$$

$$\lim_{\theta\to-\infty}\frac{\psi(\theta)}{\gamma(\theta)} = -\lim_{\theta\to-\infty}\frac{(1+\beta\theta)e^{-\theta}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}} = 1,$$

$$\lim_{\theta\to-\infty}\frac{\chi(\theta)}{\gamma(\theta)}\cdot e^{-\theta(q_1-q)} = \lim_{\theta\to-\infty}\frac{(1-\beta\theta)e^{\theta(q_1-q-2)}}{(1-\beta\theta)e^{2\theta}-(1+\beta\theta)} = 0,$$

$$q > q_{\text{`}} - 2.$$

Therefore, first composed in the right part (22) it is equal $f_0(x)$, second composed equally in zero, i.e. $\mathcal{V}(x,0) = f_0(x)$ – the entry condition is satisfied.

Thus, the solution of a task (5) - (8) will register the following a look in (14), considering (18) and (19):

$$\mathcal{V}(x,\tau) = E_{\theta}E_{\omega}\left[\frac{\varphi(\theta,\omega)e^{\omega\tau}}{\Phi(\theta,\omega)}\cdot\frac{\mathcal{X}(x)}{\mathfrak{D}(\theta)}\right],$$

$$\varphi(\omega,\theta) = (\theta+h)\int_0^1(1-\theta^2\eta)\cdot f_0(q)\cdot e^{\theta(1-q)}dq,$$

$$\Phi(\omega,\theta) = \omega(1-\theta^2\eta_1)-\theta^2,$$

$$\mathcal{X}(x) = (\beta\theta-1)e^{\theta x}+(\beta\theta+1)e^{-\theta x},$$

$$\mathfrak{D}(\theta) = (\beta\theta+1)e^{-0}-(1-\beta\theta)e^{\theta},$$

$$\mathcal{V}(x,\tau)=\underset{\theta}{E}\frac{(1-\beta\theta)e^{\theta x}-(1+\beta\theta)e^{-\theta x}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot(\theta+h)\int_0^1\left(1-\theta^2\eta\right)e^{\theta(1-q)}f_0(q)dq\times$$

$$\times\underset{\omega}{E}\frac{e^{\omega\tau}}{\omega\left(1-\theta^2\eta_1\right)-\theta^2}.$$

Let's take deduction on ω from the last factor

$$\underset{\omega}{E}\frac{e^{\omega\tau}}{\omega\left(1-\theta^2\eta_1\right)-\theta^2}=\frac{e^{\omega_0\tau}}{1-\theta^2\eta_1},$$

where $\omega_0=\dfrac{\theta^2}{1-\theta^2\eta_1}$, from here

$$\mathcal{V}(x,\tau)=\underset{\theta}{E}\frac{(1-\beta\theta)e^{\theta x}-(1+\beta\theta)e^{-\theta x}}{(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}}\cdot(\theta+h)\int_0^1 e^{\theta(1-q)}f_0(q)\,dq\cdot e^{\frac{\theta^2}{1-\eta_1\theta^2}\cdot\tau}. \quad (23)$$

Deduction on θ undertakes on those values θ, for which denominator

$$z(\theta)=(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}=0. \qquad (24)$$

From here $(1-\beta\theta)e^{\theta}-(1+\beta\theta)e^{-\theta}=0, \quad \theta=0.$

We will look for other roots in the field of complex values, i.e.

$\theta=x+iy.$

The equation (24) is equivalent to the equation

$$\beta(x+iy)\cdot\left(e^{x+iy}+e^{x-iy}\right)-\left(e^{x+iy}-e^{x-iy}\right)=0. \quad (25)$$

After division of the valid and imaginary part instead of (25) we will receive the system of the equations:

$$\begin{cases}\beta x\left(e^{x}+e^{-x}\right)-\left(e^{x}-e^{-x}\right)-\beta y\cdot tgy\left(e^{x}-e^{-x}\right)=0,\\ \beta x\left(e^{x}-e^{-x}\right)-\left(e^{x}+e^{-x}\right)+\beta y\cdot tgy\left(e^{x}+e^{-x}\right)=0,\end{cases}$$

or

$$\begin{cases}\beta y\cdot tgy=\beta x\cdot\dfrac{e^{x}+e^{-x}}{e^{x}-e^{-x}}-1,\\ \dfrac{\beta y}{tgy}=1-\beta x\cdot\dfrac{e^{x}-e^{-x}}{e^{x}+e^{-x}}.\end{cases} \qquad (26)$$

The left parts of both equations have identical signs, and the right parts are different signs therefore x it can be only identically equal to zero, and then the first equation (26) is carried out identically, and from the second equation (26) are defined:

$$\beta \cdot \frac{y \cos y}{\sin y} = 1,$$

or $\beta y \cos y = \sin y.$

Thus, we showed that roots of the equation (25) purely imaginary, i.e.

$\theta = iy$ or $z = i\lambda,$ where λ - equation roots

$$\beta\lambda \cdot \cos\lambda - \sin\lambda = 0. \quad (27)$$

In (23) deduction on θ undertakes at values $\theta = 0,\ \theta = i\lambda.$ The equation (27) is relative λ decides or in number, or using the iterative procedure.

For calculations of deductions we will take, a derivative on $\theta,$ from expression (24). Let's calculate $z'(\theta)$ at $\theta = 0$: $z(0) = 2 - 2\beta.$ Substituting value in decomposition (23) $\theta = 0$ taking into account $z'(0) \neq 0,$ let's receive corresponding to it composed, equal to zero. On roots $\theta = i\lambda$ we will present expression (23) in the row form:

$$\mathcal{V}(x,\tau) = \sum \frac{(1 - i\beta\lambda)e^{ix\lambda} - (1 + i\beta\lambda)e^{-ix\lambda}}{e^{i\lambda}(1 - i\beta\lambda - \beta) + e^{-i\lambda}(1 + i\beta\lambda - \beta)} \cdot e^{-\frac{\lambda^2}{1+\eta_1\lambda^2}\cdot\tau} \cdot (i\lambda + h)\int_0^1 f_0(q) e^{i\lambda(1-q)} dq.$$

After the corresponding transformations with use of a formula $e^{ix} = \cos x + i \sin x,$ let's receive

$$z'(\theta) = e^{\theta}(1 - \beta\theta - \beta) + e^{-\theta}(1 + \beta\theta - \beta),$$

$$z'(i\lambda) = 2(1-\beta)\cos\lambda + 2\beta\lambda\sin\lambda = \frac{2\beta\lambda - (2\beta - 1)\sin 2\lambda}{\sin\lambda}.$$

And expression (23) will be presented in following a final look:

$$\mathcal{V}(x,\tau) = \sum_{n=1}^{\infty} \frac{4(\sin\lambda_n x - \beta\lambda_n \cos\lambda_n x)\sin\lambda_n}{(2\beta - 1)\sin 2\lambda_n - 2\beta\lambda_n} \cdot e^{-\frac{\lambda_n^2}{1+\eta_1\lambda_n^2}\cdot\tau} \times$$

$$\times \int_0^1 f_0(q)\left[h \sin\lambda_n(1-q) + \lambda_n \cos\lambda_n(1-q)\right] dq,$$

where λ_n - positive roots of the equation (26). Let's come back to (9):

$$\mathcal{R}(x,\tau) = \frac{\beta - x}{\beta - 1} + p_{01}\frac{x - \beta}{\beta - 1} + \sum_{n=1}^{\infty} \frac{16(\sin\lambda_n x - \beta\lambda_n \cos\lambda_n x)\sin\lambda_n}{(2\beta - 1)\sin 2\lambda_n - 2\beta\lambda_n} \times$$

$$\times e^{-\frac{\lambda_n^2}{1+\eta_1\lambda_n^2}\cdot\tau} \cdot \int_0^1 f_0(q)\left[h \sin\lambda_n(1-q) + \lambda_n \cos\lambda_n(1-q)\right] dq + p_{01}.$$

Results and conclusions. Thus, the decision describing distributions of pressure in jointed and porous layer taking into account influence of gallery at the mode of its work set on the mouth is received. For approbation of the considered method, we will solve one more problem about hydraulic blow in the long pipeline. All procedures for Cauchy's method repeat during the solution of this task. The task about water hammer of viscous liquid in the simple pipeline is described by the equations /3/:

$$\begin{cases} -\dfrac{\partial P}{\partial x} = \rho\left(\dfrac{\partial w}{\partial t} + 2aw\right), \\ -\dfrac{\partial P}{\partial t} = \rho c^2 \dfrac{\partial w}{\partial x}. \end{cases} \qquad (28)$$

where P - pressure, w - speed of the movement of liquid under conditions:

$$t = 0, \quad w = 0, \quad P = 0;$$
$$x = 0, \quad P = 0;$$
$$x = l, \; w = A, \; A - const.$$

Having excluded from (28) pressure, we have:

$$\frac{\partial^2 w}{\partial t^2} + 2a\frac{\partial w}{\partial t} = c^2 \frac{\partial^2 w}{\partial x^2}.$$

Let's solve it under conditions:

$$t = 0, \quad w = 0, \quad \frac{\partial w}{\partial t} = 0;$$
$$x = 0, \quad \frac{\partial w}{\partial x} = 0;$$
$$x = l, \quad w = A.$$

Let's receive the decision for $P(x,t)$:

$$P(x,t) = -2a\rho A + 8\rho\frac{lA}{\pi^2}e^{-at}\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n-1)^2}\left[\frac{b_n^2 - a^2}{b_n}\sin b_n t -\right.$$
$$\left.-2a\cos b_n t\right]\sin\left(\frac{2n-1}{2}\cdot\frac{\pi x}{l}\right).$$

In work /3/ this task are solved by Fourier's method and just the same decision is received. In both tasks, apparently, this method supplements Fourier's method just in that place which makes its weak point, i.e. in satisfaction to entry conditions when the set function had to be presented in the form of the infinite series located on the known functions depending on roots of the transcendental equation. Proceeding from it, it is also possible to use it a method in approximate engineering calculations.

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