PERTURBATION OF BOUNDARY SHAPE IN CONTINUUM MECHANICS (REVIEW)

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INTRODUCTION

A number of the more effective and widely used approximate analytical methods that have been applied in continuum mechanics and in applied mathematics are variations of the methods of perturbation, expansion in a small parameter, successive approximations, and asymptotic methods. The mathematical foundations of these methods, and also many special results, are given in the monographs by Vorovich, Aleksandrov, and Babeshko [37], Guz' and Nemish [65, 66], Ivlev and Ershov [74], Il'yushin [75], Kantorovich and Krylov [80], Kauderer [81], Kayuk [82], Kosmodamianskii [86-88], Cole [90], Krylov [242], Lekhnitskii [106, 107], Lomakin [109, 110], Morse and Feshbach [127], Nyfe [130, 131], Nemish and Bloshko [180], Nemish and Chernopiskii [205], Savin [230, 232], Svirskii [240], Khusu, Vitenberg, and Pal'mov [261], Tsurpal [272], etc. Large bibliographies are contained in the review articles [89, 98, 128, 162, 274, 307], and others. Among the various methods we concentrate in the present review on the method of perturbation of boundary shape (more than twenty years ago a perturbation method under this name was introduced into the literature and applied to the solution of boundary-value problems in continuum mechanics). As noted in the review by Prokopov [226] of the monograph [66], perturbation methods "have been used repeatedly in several branches of theoretical mechanics (celestial mechanics, theory of vibrations, stability of motion), but its application to boundary-value problems is new."

As far as we know, one of the first works in this direction was [40], in which an approximate analytical method was discussed for finding the stress concentration near curved apertures in thin shells. It was later shown [52-54, 141, 145, 156] that since the method was independent of the equations of state, equilibrium, and motion, it could be applied without fundamental change to a wide class of problems in continuum mechanics. It was later extended [98] to nonlinear problems (the theory of bending of plates and shells, two-dimensional and three-dimensional problems), dynamical problems (in particular, steady-state diffraction problems, two-dimensional streamlining of noncircular cylindrical bodies by a viscous fluid, emission of sound by noncircular cylindrical shells in a fluid), two-dimensional problems in the moment theory of elasticity, and three-dimensional elastic problems for noncanonical regions. In the monographs [65, 66] this approach was called the first variant of the method of perturbation of boundary shape. It applies in cases when the boundary of the region under consideration coincides with coordinate curves (or a coordinate surface) of the orthogonal curvilinear coordinate system used in the problem.

The second variant of the method of perturbation of boundary shape was worked out in [151, 158, 169, 171] and applied to the solution of three-dimensional problems of the theory of elasticity for axisymmetric and nonaxisymmetric bodies whose surfaces do not coincide with the coordinate surfaces of the coordinate system used in the problem. It also does not depend on the equations of state, equilibrium, and motion, and therefore can be applied to a wide class of boundary-value problems in continuum mechanics. Recently it has been extended to boundary-value problems of statics for corrugated bodies, piecewise-homogeneous bodies with noncanonical dividing surfaces, elastic bodies of finite size, and structural elements with grooves and ridges and to boundary-value problems for heat conduction and thermoelasticity for noncanonical regions. We note that additional applications of the method of perturbation of boundary shape occur when it is combined with other analytical (or numerical) methods. Examples include boundary-value problems of the mechanics of deformable bodies of noncanonical shape with more complicated rheological properties. It has been applied in combination with perturbation of elastic properties [143, 146-150, 239] to the solution of boundary-value problems for physically nonlinear [68, 144, 145, 236, 272, 274] and orthotropic [160] bodies, in combination with the method of superposition to cylindrical

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bodies of revolution of finite size [20-22, 177-182] and in combination with the Laplace transform with respect to time to the solution of unsteady problems involving the saturation of a medium with finite and infinite noncanonical cavities [76, 77, 185, 258-260, 286-289].

The purpose of the present review is to give a short exposition of the mathematical foundations of these two variants of the method of perturbation of boundary shape, and also a summary of the numerous special results, along with an analysis of the effectiveness of these approaches in different branches of continuum mechanics.

We note that the necessity of a summary of the results and a writing of this review became apparent during our preparation of the manuscript "Perturbation of boundary shape in continuum mechanics," which was presented for publication to "Vishcha Shkola." It is a continuation of the review articles [98, 162, 307], which were concerned with an analysis of the research based on the different variants of the perturbation method in various branches of the mechanics of a solid deformable body.

1. MATHEMATICAL FOUNDATION OF THE METHOD OF PERTURBATION OF BOUNDARY SHAPE

First Variant of the Method. This variant of the method of perturbation of boundary shape was discussed in [40] in connection with the solution of two-dimensional boundary-value problems for the stress around nearly circular apertures in thin tapered spherical shells. Its extension to three-dimensional elastic problems for noncanonical regions was considered in [52-54, 141, 145, 152, 153, 156, 160]. Moreover, using the transformation formulas of [129] for a second-rank tensor σ, a vector u, and an arbitrary scalar function Φ under a change of orthogonal curvilinear coordinates from α_1, α_2, α_3 to α_1', α_2', α_3'

$$\sigma_{i'j'} = \sum_{k=1}^{3}\sum_{s=1}^{3} \lambda_{i'k}\lambda_{j's}\sigma_{ks};\ u_{j'} = \sum_{k=1}^{3} \lambda_{j'k}u_k\ (\Phi' = \Phi), \tag{1.1}$$

it is not difficult to note the mathematical characteristics of many two-dimensional and three-dimensional boundary-value problems in continuum mechanics for noncanonical regions [52].

Following [65, 66], we assume that the boundary S of the body under consideration can be described with the help of the function

$$\omega(\zeta) = r_0[\zeta + \varepsilon f(\zeta)]\ (|\varepsilon| \ll 1;\ \zeta = \rho e^{i\gamma}), \tag{1.2}$$

which conformally maps the exterior $|\zeta| \geq 1$ (interior $|\zeta| \leq 1$) of a unit circle to the exterior (interior) of a contour Γ. Then there are the following possible cases: a) the curve Γ bounds the exterior (or interior) of a plane (or nearly plane) region; b) the curve Γ describes the cross section of a noncircular cylindrical surface bounding the exterior or interior of a finite or infinite body; c) the curve Γ describes the meridian cross section of a closed surface of revolution which bounds the exterior or interior of a finite or infinite body; d) the curve Γ corresponds to one of the last three cases, but forms the boundary dividing two continuous media with different physical and mechanical properties.

The direction cosines $\lambda_{j'k}$ of the angles between the unit vectors $\vec{e}_{j'}$ and $\vec{e}_k$ ($j' = \alpha_1'$, α_2', α_3'; $k = \alpha_1$, α_2, α_3) can be expressed in terms of the angle β between the radial direction and the normal to the contour Γ. This angle is related to the function $\omega(\zeta)$ by the formula $e^{i\beta} = \zeta\bar{\omega}\omega'/|\zeta||\omega||\omega'|$ (here a prime denotes the derivative with respect to ζ).

In the three-dimensional case, on the boundary S of the body (ρ = const) either the external force $\sigma_{\rho j'}|_S = \sigma_{j'}^0$ can be specified, or the vector $u_{j'}|_S = u_{j'}^0$, or the scalar function $\Phi'|_S = \Phi^0$, or its normal derivative $\partial\Phi'/\partial\rho|_S = \Phi_*$. Various mixed conditions are also possible and can be written as different combinations of these equations.

Tensor, vector, and scalar quantities correspond to different physical and mechanical characteristics in the different branches of continuum mechanics. These characteristics are determined by the effect of certain operators on functions satisfying appropriate differential equations (in the usual cases one deals with Laplace's equation, the biharmonic equation, the Helmholtz equation and combinations of these equations in rectangular, spherical, and circular cylindrical coordinates). However, the equations of equilibrium or equations of motion of most continuous media (in terms of the variables $\alpha_{1'}$, $\alpha_{2'}$, $\alpha_{3'}$) are quite complicated and it is usually not possible to obtain an exact analytical solution using separation of variables.

Therefore, the components of the second-rank tensor $\sigma_{i'j'}$, the vector $u_{j'}$, and the scalar function Φ' are expanded in series form

$$\{\sigma_{i'j'}, u_{j'}, \Phi'\} = \sum_{n=0}^{\infty} \varepsilon^n \{\sigma_{i'j'}^{(n)}, u_{j'}^{(n)}, \Phi'^{(n)}\}. \tag{1.3}$$

Using the transformation equations (1.1), the expression for the direction cosines $\lambda_{j'k}$ in terms of the function (1.2), and the expansions (1.3), we obtain the following recursion relations for the components in the n-th approximation. For the second-rank tensor

$$\begin{gathered}\sigma_{1'1'}^{(n)} = \sum_{m=0}^{n} [L_1^{(n-m)}\sigma_{11}^{(m)} + L_2^{(n-m)}(\sigma_{22}^{(m)} - \sigma_{11}^{(m)}) + L_3^{(n-m)}\sigma_{12}^{(m)}];\\ \sigma_{2'2'}^{(n)} = \sum_{m=0}^{n} [L_1^{(n-m)}\sigma_{22}^{(m)} - L_2^{(n-m)}(\sigma_{22}^{(m)} - \sigma_{11}^{(m)}) - L_3^{(n-m)}\sigma_{12}^{(m)}];\\ \sigma_{1'2'}^{(n)} = \sum_{m=0}^{n} [L_2^{(n-m)}\sigma_{12}^{(m)} + L_4^{(n-m)}(\sigma_{22}^{(m)} - \sigma_{11}^{(m)})];\end{gathered} \tag{1.4}$$

for the vector

$$\begin{gathered}u_{1'}^{(n)} = \sum_{m=0}^{n} [L_5^{(n-m)}u_1^{(m)} + L_6^{(n-m)}u_2^{(m)}];\\ u_{2'}^{(n)} = \sum_{m=0}^{n} [L_5^{(n-m)}u_2^{(m)} - L_6^{(n-m)}u_1^{(m)}];\end{gathered} \tag{1.5}$$

and for the arbitrary scalar function

$$\Phi'^{(n)} = \sum_{m=0}^{n} L_1^{(n-m)}\Phi^{(m)}. \tag{1.6}$$

Here the $L_i^{(m)}$ are differential operators which depend on the form of the function $f(\zeta)$; expressions for these operators have been given for an arbitrary order of approximation in [65, 66, 153].

Note that the components $\sigma_{1'3'}^{(n)}$, $\sigma_{2'3'}^{(n)}$ are given by formulas of the type (1.5), while $\sigma_{3'3'}^{(n)}$, $u_{3'}^{(n)}$ are given by (1.6).

An important feature of the first variant of the method of perturbation of boundary shape is that the tensor $\sigma_{ks}^{(m)}$ $(\rho, \gamma, \alpha_{3'})$, vector $u_s^{(m)}$ $(\rho, \gamma, \alpha_{3'})$, and scalar $\Phi^{(m)}$ $(\rho, \gamma, \alpha_{3'})$ quantities on the right-hand sides of (1.4)-(1.6) are written by formally replacing circular cylindrical coordinates r, θ, z (or spherical coordinates r, θ, α) by noncircular cylindrical coordinates ρ, γ, ξ (or the coordinates defined by the body of revolution ρ, γ, φ). This is an important feature in the solution of boundary-value problems in continuum mechanics, because it allows one to use the known equations and functions in circular cylindrical or spherical coordinates to immediately write down the corresponding equations and functions in the actual orthogonal curvilinear coordinate system being used, to any order of approximation.

Hence, this variant of the method can be used directly if the above tensor, vector, and scalar quantities are identified with specific physical and mechanical characteristics consistent with the formulation of the boundary-value problem, which in turn corresponds to some model in continuum mechanics.

A significant extension of this approach was obtained in the solution of boundary-value problems in the dynamics of noncircular shells in fluids [33-36], in which the boundary conditions are different from those discussed above in that they contain higher-order differential operators with variable coefficients. For example, an m-th order differential operator has the form

$$\left(\frac{1}{B}\frac{\partial}{\partial\gamma}\right)^{(m)}=\sum_{k=1}^{m}\left[\sum_{j=0}^{\infty}\varepsilon^{j}\ A_{kj}^{(m)}(\gamma)\right]\frac{\partial^{k}}{\partial\gamma^{k}}\ (m=1,\,2,\,4). \tag{1.7}$$

Here B is the coefficient of the first quadratic form and depends on the function (1.2) which describes the contour of the cross section of the noncircular cylindrical shell.

Boundary conditions corresponding to the three cases discussed above have the following simple forms in the variables ρ, γ, $\alpha_{3'}$, in an arbitrary order of approximation: For stresses specified on S

$$\sigma_{\rho j'}^{(n)}|_{\rho=\mathrm{const}}=\sigma_{j'}^{0(n)}\ \ (j'=\rho,\,\gamma,\,\alpha_{3'}); \tag{1.8}$$

for components of the displacement or velocity specified on S,

$$u_{j'}^{(n)}\,|_{\rho=\mathrm{const}}=u_{j'}^{0(n)}; \tag{1.9}$$

and for the scalar function or its derivative given on S,

$$\Phi^{'(n)}|_{\rho=\mathrm{const}}=\Phi^{0(n)};\ \ \frac{\partial}{\partial\rho}\Phi^{'(n)}|_{\rho=\mathrm{const}}=\Phi_{*}^{(n)}. \tag{1.10}$$

Second Variant of the Method. The second variant of the method of perturbation of boundary shape was developed in [151, 158, 169, 171]. The essence of this method is as follows. Let the boundary of a continuous medium in orthogonal curvilinear coordinates α_1, α_2, α_3 be described by the equation

$$\alpha_1=\alpha_0+\varepsilon f(\alpha_2,\,\alpha_3), \tag{1.11}$$

where α_0 = const ≥ 0, $f(\alpha_2, \alpha_3)$ is a known analytical function; ε is a small parameter ($|\varepsilon| \ll 1$) characterizing the deviation of the surface S under consideration from the coordinate surface $\alpha_1 = \alpha_0$.

Then from the function $F(\alpha_1, \alpha_2, \alpha_3) = \alpha_1 - \varepsilon f(\alpha_2, \alpha_3)$ it is easy to calculate the unit normal vector

$$\vec{e}_n=\frac{\nabla F}{|\nabla F|}\left(\nabla=\frac{\vec{e}_1}{H_1}\frac{\partial}{\partial\alpha_1}+\frac{\vec{e}_2}{H_2}\frac{\partial}{\partial\alpha_2}+\frac{\vec{e}_3}{H_3}\frac{\partial}{\partial\alpha_3}\right). \tag{1.12}$$

Here the H_i are the Lame parameters.

Therefore, the direction cosines n_j of the normal $\vec{n}$ to S are given by

$$n_j=\frac{1}{|\nabla F|}\frac{1}{H_j}\frac{\partial F}{\partial\alpha_j}\,. \tag{1.13}$$

The following boundary conditions can be specified on the surface S of the continuous medium: the components of the external forces $\sigma_j{}^0$

$$\sum_{k=1}^{3}\sigma_{kj}n_k\,|_S=\sigma_j^0\ \ (j=1,\,2,\,3); \tag{1.14}$$

the components of the displacement vector (or velocity vector) $u_j{}^0$

$$u_j\,|_S=u_j^0; \tag{1.15}$$

the scalar function Φ^0

$$\Phi\,|_S=\Phi^0; \tag{1.16}$$

or the normal derivative Φ_* of the scalar function

$$\frac{\partial}{\partial n}\Phi|_S = \Phi_*. \tag{1.17}$$

Even though in such often-used orthogonal coordinate systems as rectangular, circular cylindrical, and spherical, in which the general analytical solution of the equations of equilibrium and motion can be obtained for most models of continuous media by means of separation of variables, the complexity of the boundary surface S described by an equation of the type (1.11) means that one cannot obtain an exact analytical solution of the boundary-value problem because of the complexity of the boundary conditions of the types (1.14)-(1.17). For this reason the solution of the boundary-value problem is sought in the form of series of the type (1.3). Assuming that the unknown tensor, vector, and scalar quantities can be expanded in Maclaurin series about the coordinate surface $\alpha_1 = \alpha_0$, we obtain

$$\{\sigma_{ks}, u_k, \Phi\}_S = \sum_{n=0}^{\infty} \varepsilon^n \sum_{m=0}^{n} \{L^{(m)} [\sigma_{ks}^{(n-m)}, u_k^{(n-m)}, \Phi^{(n-m)}]\}_{\alpha=\alpha_0}, \tag{1.18}$$

where $L^{(m)}$ is a differential operator of order m.

Therefore, from (1.14)-(1.17) the boundary conditions in an arbitrary order of approximation reduce to the form

$$\sum_{k=1}^{3} \sum_{m=0}^{n} N_k^{(n)} \sigma_{kj}^{(n-m)} |_{\alpha=\alpha_0} = \sigma_j^{0(n)} \quad (j = \alpha_1, \alpha_2, \alpha_3); \tag{1.19}$$

$$\sum_{m=0}^{n} L^{(m)} u_j^{(n-m)} |_{\alpha=\alpha_0} = u_j^{0(n)}; \tag{1.20}$$

$$\sum_{m=0}^{n} L^{(m)} \Phi^{(n-m)} |_{\alpha=\alpha_0} = \Phi^{0(n)}; \tag{1.21}$$

$$\sum_{k=1}^{3} \sum_{m=0}^{n} N_k^{(n)} \frac{1}{H_k} \frac{\partial}{\partial \alpha_k} \Phi^{(n-m)} |_{\alpha=\alpha_0} = \Phi_*^{(n)}. \tag{1.22}$$

Here the $N_k^{(n)}$ are differential operators whose analytical structure depends on the form of Eq. (1.11) describing the geometry of the surface S. These operators, in an arbitrary order of approximation, have been obtained in rectangular coordinates [167, 169, 175], in circular cylindrical coordinates [151, 158], and in spherical coordinates [158, 170, 171].

This approach has made it possible to consider a series of new problems involving axisymmetric and nonaxisymmetric bodies bounded by surfaces that are nearly coordinate planes [179, 180] or nearly the coordinate surfaces of circular cylindrical and spherical coordinate systems [65, 66, 180, 208].

Hence the essence of the first (for orthogonal boundaries) and second (for nonorthogonal boundaries) variants of the method of perturbation of boundary shape is the reduction of a boundary-value problem for a noncanonical region to a series of boundary-value problems for canonical regions which are close to the original noncanonical region, and the corrections in the successive approximations appear only in the boundary conditions. Thus there are no additional difficulties in constructing the general and particular solutions of the equations of equilibrium or motion for a continuous medium and also there is the possibility of extending this method to a wide class of boundary-value problems in continuum mechanics.

2. MECHANICS OF A DEFORMABLE SOLID BODY

Analysis of the research up to 1981 in the field of boundary-value problems in the mechanics of deformable bodies involving the method of perturbation of boundary shape has been given in the review articles [98, 162, 307]. The research covers the following branches: three-dimensional elastic problems for noncanonical regions [79, 83, 84, 115-118, 120, 133-136, 141, 142, 151-194, 198-209, 221-225, 253-256, 277, 278, 298, 301, 303, 308]; problems involving the stress concentration near curved apertures in cylindrical, spherical, and conical shells [17, 18, 38, 40-51, 60, 64, 67, 69-73, 99, 111-114, 216-218, 220, 227-229, 231-234, 237, 243, 246-248, 279, 280, 290-292, 297, 308, 309]; dynamical elastic problems for noncanonical regions (three-dimensional [52-54, 61, 62, 174] and two-dimensional [63, 93-97, 105, 252, 302]); two-dimensional problems in the theory of elasticity and thermoelasticity in the classical and refined formulations for regions with curved apertures and inclusions [16, 59, 85, 89, 91, 92, 102, 137-140, 210-213, 230, 235, 238, 250, 251; 261, 299, 304]; problems involving the bending of plates with curved inhomogeneities in the nonclassical formulation [122, 124, 195-197, 214-216, 249, 310]; physically nonlinear problems (three-dimensional [144, 145]; two-dimensional [1-4, 15, 28-32, 68, 100, 101, 126, 236, 262-275], bending of plates [293-296], theory of shells [126, 236, 275, 276]).

In this section we discuss only those papers in the mechanics of deformable solid bodies which involve the method of perturbation of boundary shape, and which were published in the last few years (supplemented by some earlier publications).

Mechanics of Piecewise-Homogeneous Bodies with Noncanonical Surfaces. The branches of the mechanics of deformable bodies mentioned above, although relevant to the subject of this section, will not be analyzed here, since they have been reviewed in [98, 162, 307]. Here we will consider mainly boundary-value problems for deformable bodies with noncanonical cavities, elastic or rigid inclusions, and also for layered media with surfaces between the layers which are nearly plane, cylindrical, spherical, or conical.

Piecewise-homogeneous bodies with noncanonical surfaces between layers are diverse in nature. They include mountain massifs with noncanonical shafts and foreign strata, composite (granular, layered, or fibrous) materials with small-scale deviations in structure, etc. A wavy surface in materials composing certain products and elements of construction is technologically unavoidable in many cases. An example is the explosive welding of materials [104, 241]. The mechanism of formation of wavy surfaces has been discussed in [125, 306]. It is important in practice that the characteristics of a wavy boundary between two neighboring layers, which essentially determines the strength of the welded joint, can be controlled [104]. Multilayered elements of construction (in particular bellows [242]) are used in practice to increase strength and as a defense against corrosion.

The papers [133-136, 141, 145, 191-194] are relevant to this subject. In these papers analytical solutions were obtained for three-dimensional axisymmetric elastic problems for isotropic and transversely isotropic media (spherical isotropy) with closed noncanonical cavities and rigid inclusions under torsion [134, 191] or uniform expansion (contraction) [133, 136, 192-194]. Numerical solutions were obtained to second or third order in a small parameter characterizing the deviation of the boundaries from spheres. The boundary surfaces were obtained by rotating an equilateral triangle, square, or pentagon about the axis of symmetry. The effect of the curvature of the surface and the elastic properties of the medium on the stress concentration near noncanonical surfaces was established. The distribution of maximum stress along characteristic directions is highly local in nature, such that when one moves away from the unstressed surface of a noncanonical cavity by approximately two dimensionless radii, the deviation of the stress from the nominal does not exceed 2%.

The vibrations of a rigid inclusion in the shape of an oblate body of revolution was studied in [301] using the small parameter method, where the small parameter characterized the deviation from a sphere. The axisymmetric case was discussed in detail and possible extensions of the method to nonaxisymmetric problems were analyzed.

The axisymmetric stress of an isotropic medium with an isotropic elastic noncanonical inclusion was considered in [198] for the case of a biaxial elongation (compression) "at infinity." The stress distribution inside the inclusion and in the medium was studied as a function of the ratio of the shear moduli of the two media and the static loads in two mutually perpendicular directions.

It was assumed that the surface can be described by an equation of the type (1.1) with $f(\theta) = \cos 2\theta$. The results were compared with the known exact solution for a medium with an ellipsoidal cavity in a special case in [281].

Analogous studies have been done for the case when the isotropic medium with a noncanonical cavity is a reinforced thick isotropic elastic shell [199, 200]. It is assumed that ideal contact exists on the surface. From this solution results for a medium with an elastic inclusion [281], a perfectly rigid inclusion, and with a stress-free noncanonical cavity [39] follow as special cases. The cases of uniform isotropic expansion (compression) [199] and nonuniform loading [200] were both considered.

The stress distribution in geometrically different reinforcing elements and in the external medium was studied as a function of the ratio of the shear moduli of the two media and the thickness of the reinforcement. It was shown that the rigidity of the reinforcement lowers the stress concentration on the surface of the noncanonical cavity.

The stress caused by a slightly nonspherical elastic inclusion in an unbounded matrix was determined in [303]. In addition to the case of ideal contact, the case was considered where the tangential stress is zero on the surface of the inclusion, while the normal component of the displacement vector is continuous across the surface (the case where the inclusion slips without separating).

In [298] the analogous two types of boundary-value problems were considered for an elastic medium with a noncircular cylindrical inclusion.

Both variants of the method of perturbation of boundary shape (for orthogonal and nonorthogonal surfaces) have been applied to the solution of three-dimensional boundary-value problems for multilayered bodies (such as thick-walled shells) whose surfaces are nearly spherical [164] and nearly circular cylindrical [163]. This approach was used to study the static stress of isotropic and transversely isotropic bilayered and trilayered transversely corrugated [120-121, 190, 205] and longitudinally corrugated [189] thick-walled cylinders under a radial pressure varying according to a trigonometric function. On the ends of the cylinders special mixed boundary conditions were specified, a special case of which corresponds to an infinitely long, periodically stressed cylinder.

The method of perturbation of boundary shape has been developed for three-dimensional statics problems involving multiply connected noncanonical regions [155] (for a three-dimensional medium with noncircular cylindrical cavities or inclusions lined up in a single direction and also for a medium with finite cavities or inclusions having the shape of bodies of revolution with a common axis).

In [175] an approach was presented to solving elastic boundary-value problems for piecewise-homogeneous media reinforced by elastic layers of variable thickness. The small-scale deviations of the layers from coordinate planes were described by equations for the level surface. An approximate method of solving three-dimensional boundary-value problems involving a deformable composite cone with noncanonical surfaces between the layers was discussed in [176].

An approach to the study of the thermostress in corrugated layered bodies where the surfaces between the layers are close to circular cylindrical or spherical was developed in [168, 172].

An approximation method of solving three-dimensional elastic problems for nearly spheroidal (ellipsoid of revolution) bodies was worked out in [221, 223]. The method was used to study the stress near a short rigid cylindrical inclusion soldered into a matrix [224].

Various problems involving the mechanics of composite materials with small-scale structural distortions fall into the same category. Problems of this kind are solved using the model of a piecewise-homogeneous medium. Also boundary-value problems in the theory of gas-saturated media with noncanonical cavities fall into this category. The next two sections review the research in these two areas.

<u>Mechanics of Composite Materials with Small-Scale Structural Distortions</u>. The study of strength, stability, and vibration of composite materials with small-scale structural distortions (and of structural elements made from materials of this type) requires rather complete information on the stress and deformation of the material. Small-scale structural distortions of composite materials is usually understood to mean deviations from some ideal structure such that the size of the deviations is much smaller than that of the structural elements of these materials under consideration.

The continuum theory of composite materials with small-scale distortions in a regular structure was developed in [55-58]. It gives a possible explanation of a well-known phenomenon in the mechanics of the breakdown of unidirectional composite materials. This is the "shredding" effect. It occurs when there is a uniaxial load along the reinforcing elements and the composite material separates into threads (fibers) and strands and the solidity of the material is lost.

However, in most cases the continuum theory [55-58] cannot give sufficiently complete and reliable quantitative information on the stress and deformation distributions in each of the components of the composite material. The stress and deformation of a composite material with small-scale structural distortions has been considered in [5-14] using the piecewise-homogeneous model. An effective method was given for solving three-dimensional elastic boundary-value problems for piecewise-homogeneous layered [10] and fibrous [11] materials with elastic components. This approach was extended to piecewise-homogeneous viscoelastic media in [7]. These studies have assumed a small concentration of sealer, when the interference of neighboring distortions of the layers or fibers of the sealer are not taken into account in an essential way. Using the method of [10] and the model of a piecewise-homogeneous model, the same problem was studied in [13], but the interference of all of the layers of the sealer was fully taken into account. On this basis the results of the continuum theory were defined [55-58].

Unsteady Theory of Gas-Saturated Media with Noncanonical Cavities. The system of equations of [257] form the groundwork in this field. These equations describe the coupling between the deformation of a gas-saturated porous medium and filtration of gas in the linear approximation. The analytical solutions of boundary-value problems have been used to study the stress and strength of mountain massifs near finite and infinite shafts of noncanonical shapes. These studies used the first variant of the method of perturbation of boundary shape (Sec. 1), along with the Laplace transform with respect to time.

In particular, the two-dimensional stress and strength of a gas-saturated massif has been studied for the case of an infinitely long cylindrical shaft of elliptical [76] and square [258] cross section. The case of a cylindrical shaft with a cross section in the shape of a regular polygon with rounded corners was considered in [77].

The boundary-value problems were solved for the case when the stress of the unbroken porous gas-saturated massif is biaxial; a special case is a hydrostatic pressure. The stability criterion of the solid phase was taken in the form [219].

Actual numerical results were obtained for shafts of elliptical and square (with rounded corners) cross sections in a coal massif saturated with methane.

Coupled two-dimensional problems for the stress of saturated porous massifs with horizontal cylindrical shafts with curved cross sections were formulated and solved in [185, 186]. In particular, it was shown that the coupling between the deformation and filtration processes affects the stress near shafts with elliptical and square cross sections.

An axisymmetric stress state and strength of a gas-saturated massif near finite shafts occurs when it is assumed that at large enough depths the biaxial stress state of the unbroken massif can, to an acceptable approximation, be replaced with an isotropic compression (hydrostatic pressure). With this assumption and the equations of [257], the boundary-value problems were solved for an ellipsoidal shaft [259, 286] and for a finite cylindrical shaft [288]. Among the most complicated of the problems in this field are three-dimensional nonaxisymmetric boundary-value problems for closed surfaces of revolution. Analytical and numerical results have been obtained for the case of a nonaxisymmetric stress state near ellipsoidal cavities and cylindrical cavities of finite length [260, 287].

The numerical results for the stress distribution near shafts obtained by solving certain boundary-value problems have been used to describe some possible ejection mechanisms.

Mechanics of Bodies of Finite Size and Structural Elements with Small Grooves. Two approaches have been typically used in the analytical solution of three-dimensional elastic boundary-value problems for bodies of finite size such that parts of the surface of the body belong to coordinate surfaces of different families. These approaches are the method of superposition and the method of homogeneous solutions. The method of superposition of Lame invariably leads to an infinite system of algebraic equations. The theory of this type of infinite system, in which the asymptotic properties of the unknown constants are of special interest, has been worked out fairly completely.

In principle, the methods of superposition and homogeneous solutions can be relied upon to obtain the solution only in those cases when parts of the boundary of the body are coordinate surfaces of different families. This is because an exact general solution of the equations of elasticity (by means of separation of variables) can be obtained only in those curvilinear coordinate systems in which the Laplace equation (statics problems) or Helmholtz equation (dynamics problems) is separable.

The subject of interest in this section is the class of boundary-value problems for solid and hollow isotropic and transversely isotropic cylindrical bodies of finite size with small grooves on the curved surface or on the ends of the cylinder. Because for bodies of this type at least one of the surfaces of the body is not a coordinate surface in cylindrical coordinates, the method of superposition or homogeneous solutions cannot be applied directly to the solution of boundary-value problems for such bodies.

An approach based on the combined application of the method of perturbation of boundary shape and the principle of superposition was used for the first time in [177] to obtain an analytical solution of the axisymmetric boundary-value problem for the stress of an elastic isotropic cylinder of finite size with transverse corrugations. In this approach the three-dimensional boundary-value problem for a finite cylinder with small grooves on the curved surface or on the ends can be reduced to a recursive sequence of boundary-value problems for a circular cylinder which is bounded by coordinate planes along the axis. Therefore, at each step of the iterative process one can use the principle of superposition (or the method of homogeneous solutions). This leads to an infinite system of algebraic equations in each of the successive approximations. The asymptotic properties of the unknowns of these systems are then studied.

Application of this approach to axisymmetric boundary-value problems for solid and hollow isotropic and transversely isotropic bodies with periodic and nonperiodic grooves on the lateral surfaces has been given in [20-22, 178] and with grooves on the end surfaces in [179]. Boundary effects in hollow cylinders with grooves caused by axisymmetric self-balancing loads applied to the ends were considered on this basis in [181].

These studies have shown that the practical convergence of the successive approximation process is fairly good [180]. We note that when the stress near the bottom of grooves in finite bodies is determined from the equations of [132], which were derived for infinite bodies, significantly underestimated results are obtained in many cases [180, 244].

3. HEAT CONDUCTION AND THERMOELASTICITY

The different variants of the method of perturbation of boundary shape have been applied to new classes of boundary-value problems in the theories of heat conduction and thermoelasticity. These problems include, in particular, three-dimensional problems for bodies with noncanonical surfaces (such as rough boundaries), problems involving thin spherical and circular cylindrical shells with curved apertures, optimization problems for plates with curved contours, etc.

Three-Dimensional Problems. In [165] boundary-value problems were considered for the heat equation involving bodies with nearly spherical surfaces. It was assumed that the coefficients of thermal expansion of the body are different in the radial and tangential directions. The following four types of boundary conditions were used, which are a certain idealization of the actual physical processes: the temperature of heat flux is specified on the surface of the body, the surface is thermally insulated, or the convective boundary condition is specified. The case of orthogonal surfaces (first variant of the method of perturbation of boundary shape) and nonorthogonal surfaces (second variant of the method of perturbation of boundary shape) were both considered. Problems of this kind reduce to a recursive sequence of boundary-value problems for spherical surfaces close to the surface of the body. Differential operators of the boundary conditions in an arbitrary order of approximation were given, allowing one to solve the problem to a required accuracy. Similar heat-conduction problems for bodies with orthogonal and nonorthogonal surfaces close to circular cylindrical were considered in [166].

This approach can be used to obtain an analytical solution in a form which is convenient for further use in the solution of boundary-value problems of thermoelasticity for noncanonical regions close to spherical or circular cylindrical [165, 166].

Stochastic problems in the theories of heat conduction and thermoelasticity for deformable bodies with irregular surfaces were considered in [282, 283] with the help of the second variant of the method of perturbation of boundary shape discussed in Sec. 1.

In [168, 172] three-dimensional boundary-value problems of heat conduction and thermoelasticity were formulated and solved for multilayered bodies with surfaces between layers that were nearly spherical or circular cylindrical. Ideal and nonideal thermal contacts between neighboring layers were considered.

For orthogonal [172] and nonorthogonal [168] surfaces between layers, the original problem was reduced to a sequence of boundary-value problems for multilayered bodies with canonical surfaces between layers.

Theory of Shells and Plates. Boundary-value problems for heat conduction and thermoelasticity in thin hollow spherical and circular cylindrical shells with curved apertures were considered in [119, 284, 285]. In particular, in [119] the steady temperature and stress fields were studied in a spherical shell with elliptical, triangular, square, pentagonal, and hexagonal apertures. In [284] an approximate analytical solution was obtained for the thermostress of a thin isotropic cylindrical shell with elliptical, square, and hexagonal apertures. It was assumed that the inner surface of the shell was thermally insulated and that there was convective heat exchange with a medium on the outer surface of the shell and on the contour of the curved aperture. The temperature field and stress of a transversely isotropic plate subjected to a thermally induced bend was studied in the monograph [215]. The method of S. P. Timoshenko was used, extended to take into account normal thermal expansion in the directions perpendicular to the plane of isotropy.

In particular, the thermostress of plates with elliptical, triangular, and square apertures was studied for the case when a bending distortion is caused by a steady temperature field varying linearly with thickness.

In [26], analytical methods of dealing with optimization problems of the stress and deformation of thin plates induced by local heating was extended to the case when the plate is subjected to a two-dimensional temperature field and the high-temperature region is bounded by a curved contour. A mathematical formulation and analytical solution of these optimization problems was worked out using methods of the calculus of variations, the theory of functions of a complex variable, and the method of perturbation of boundary shape. The paper [300] pertains to the same line of study.

4. THEORY OF EMISSION AND DIFFRACTION OF WAVES

Emission and Diffraction of Sound by Noncircular Cylindrical Shells in a Fluid. Basically two approaches have been devised to deal with the analytical solution of boundary-value problems of hydroelasticity involving shells of noncanonical shape: the method of surface integral equations and the metaharmonic potential [19, 78, 123], and the method of perturbation of boundary shape [34-36].

One of the principal advantages of the first approach is its independence of the shape of the boundary surface. However, it is very difficult to obtain analytical solutions to actual problems and it is usually necessary to resort to various approximation methods in order to obtain numerical results.

An advantage of the second approach (based on the method of perturbation of boundary shape) is that it does not depend on the equation of state and equations of motion of the shell and at each step of the iterative process the complexity of the problem remains the same as for the case of a circular cylindrical shell. Dynamics boundary-value problems involving noncircular cylindrical shells in a fluid were considered in [33-36]. Approximate analytical solutions were obtained for two-dimensional problems and the emission of sound by cylindrical shells with elliptical, triangular, and square cross sections was studied for the case when the shell is subjected to an axisymmetric excitation. Numerical values were given for the normalized pressure amplitude in the zeroth, first, and second approximations and these results indicate that the iterative process converges in the practical sense [36]. In [35] the problem for the diffraction of sound waves by an infinitely long noncircular cylindrical shell filled with fluid was solved.

It was shown that the presence of the fluid inside the shell leads to a decrease in the amplitude of the pressure in the reflected wave, since in this case energy is expended in exciting waves in the fluid inside the shell. This agrees with results known in the literature for related problems [123].

The scattering of sound by an irregular waveguide was considered in [105]. The solution was obtained by perturbation using a special choice of the starting (zero-order) approximation.

Propagation and Diffraction of Elastic Waves. The first variant of the method of perturbation of boundary shape (Sec. 1), discussed in [40], has also been extended to dynamics elastic problems. The propagation and diffraction of elastic waves was studied in [53, 54, 61-63, 91-96, 174] for bodies bounded by smooth surfaces in the shape of noncircular cylinders or surfaces of revolution.

In particular, the stress of a thin plate (generalized two-dimensional stress) with a curved aperture, where a uniform pressure harmonically varying in time was applied around the edge of the aperture, was studied in [93, 94]. It was shown that unlike the case of a circular aperture, in which the contour of the aperture emits only compressional waves, in the case of a noncircular aperture the symmetry is lost, and therefore the diverting wave field has compressional wave and shear wave components. The numerical results presented in these papers showed that there exists a frequency region in which the normal stress exceeds its static value.

The effect of plane harmonic compressional or shear waves on elliptical and square apertures in a thin plate was considered in [95, 96]. The most typical case was considered, where the aperture contour lies at a variable angle to the direction of propagation of the wave; however, there is symmetry with respect to this direction. The effect of cylindrical waves on an arclike aperture was discussed in [252] for an arbitrary location of the source.

Methods of solving three-dimensional propagation and diffraction problems in bodies with noncircular cylindrical boundaries [52] and also steady-state diffraction problems of waves by finite nonspherical bodies of revolution [53, 62, 174] are based on the corresponding results of [40, 52, 158].

A generalized treatment of the approaches to the steady-state diffraction of elastic waves for the two- and three-dimensional cases was given in the monographs [61, 63, 65] for noncanonical regions.

5. STREAMLINING OF BODIES OF NONCANONICAL SHAPES BY A VISCOUS FLUID

Boundary-value problems for the steady streamlining of bodies by a viscous fluid have been discussed in several monographs by Soviet and foreign authors. However, because the basic equations are so complicated in the general case, exact analytical solutions cannot be obtained even for a sphere or circular cylinder. Therefore, various approximation methods have been devised for bodies of canonical shape which are then used to obtain a solution with satisfactory accuracy [23-25, 27]. In [23] an approximate analytical approach to the solution of two-dimensional Oseen problems for the streamlining of noncircular cylinders by a viscous fluid was developed. The approach is based on the first variant of the method of perturbation of boundary shape (Sec. 1). The solution for a circular cylinder obtained in [24] was taken as the initial (zero-order) approximation. From the mathematical point of view this solution was constructed using rather strong simplifying assumptions; however, it agrees rather well with the experimental data, even for comparatively large Reynolds numbers.

Explicit analytical expressions for the drag coefficients were obtained in [23] for the streamlining of cylinders of elliptic, triangular, and square cross sections. Comparison of the numerical results for cylinders of the different shapes shows that the geometrical characteristics of the cylinder, and also inertial and viscous effects affect the drag coefficient of the cylinder.

6. EFFECTIVENESS OF THE METHOD OF PERTURBATION OF BOUNDARY SHAPE FOR BOUNDARY-VALUE PROBLEMS IN CONTINUUM MECHANICS

An important question for approximation methods of solving boundary-value problems in continuum mechanics is the effectiveness of the method. Even if one can prove that the method converges in the general sense by the methods of functional analysis, this does not remove the importance of studying the practical convergence of the method. The latter includes the following questions: the rate of convergence; the number of terms necessary to obtain a given accuracy; an estimate of the remaining terms of the series; and the determination of either the absolute or percent contribution of each of the computed terms in a sum of the absolute values of these terms. In addition, the effectiveness of the method can be judged by comparison with exact solutions in certain special cases, and also with experimental data, where data are available.

Comparison with Exact Solutions in Special Cases. Boundary-value problems of continuum mechanics involving regions which are nearly spherical or circular cylindrical include as special cases elliptical and ellipsoidal regions, which in many cases have exact analytical solutions. Comparison of the exact and approximate numerical values for the same boundary-value problem is a certain indication of the effectiveness of the approximate method.

For example, in [40, 70, 71] numerical values for the coefficient of stress concentration in spherical shells with curved apertures were given, along with the corresponding approximate results for plates with similar apertures and these were then compared with the exact values. It was established by comparisons of this kind that when the boundary-value problem is solved to an accuracy of $O(\varepsilon^3)$ (in comparison with unity) the error is 1.3% for a free elliptical aperture with an axial ratio of 3:2 ($\varepsilon = 0.2$) and is 5.6% for a square aperture with rounded corners ($\varepsilon = 1/9$). Approximately the same deviations are observed for plates with fortified elliptical and square apertures.

It is well known [65, 107, 132, 222, 281] that three-dimensional static elastic problems for ellipsoidal regions have exact analytical solutions. On the other hand, these problems can be solved using the method of perturbation of boundary shape, where the initial approximation is taken to be the solution of the corresponding problem for a spherical region. Therefore, the effectiveness of the method of perturbation of boundary shape can be analyzed by comparing the numerical results from the exact and approximate analytical solutions. For example, in [141, 191] the exterior problem was solved for the stress of a medium with an ellipsoidal cavity of eccentricity $\varepsilon = (a - b)/(a + b)$ under applied torsion or compression (a and b are the half-axes of the ellipsoid). Exact solutions of these problems are given in [107, 132, 281], for example. Comparison of the numerical values shows that the error (in comparison with the exact solution) does not exceed 3% for $|\varepsilon| \lesssim 1/3$ (torsion) and $|\varepsilon| \leq 0.268$ (compression or elongation).

The symmetric deformation of a thin isotropic ellipsoidal shell under internal pressure was considered in [117]. The exact solution of the problem was obtained in [103]. It was shown that when the surfaces of the shell approach one another (the thickness parameter ρ_0 decreases) the mutual effect of the surfaces is amplified and the error in the method increases somewhat. However, in the interval $1.01 \leq \rho_0 \leq 3.00$ it does not exceed 3.6%, even though the difference between the numerical results for an ellipsoidal shell and those for a complete sphere reaches 32% for comparatively thin shells ($1.0 \leq \rho_0 \leq 1.05$) and increases with increasing thickness.

If an exact analytical solution is not available, an indication of the effectiveness of the approximate analytical methods can be obtained by comparison of the approximate numerical results with experimental data, as was done in [180] in a study of the axisymmetric stress state of a finite solid isotropic cylinder with two circular grooves under a constant axial compression. A similar comparison was done in [180] for a complete cylinder with four circular grooves. We note that the stress concentration coefficient calculated from the equations of [132] for an infinite cylinder underestimates the true value by about 20-23%. This conclusion is also supported by the numerical results obtained in [244].

Practical Convergence. As far as we know there has been no study of the convergence of the method of perturbation of boundary shape using functional analysis. However, in some special cases (and with certain assumptions) the first few terms of the series have been used to get an estimate of the remainder, and also the number of terms in the series necessary to attain a given accuracy [65, 66, 52]. Based on these results a majorant series can be constructed which gives an estimate of the original series. The estimate improves in accuracy the larger the number of known terms.

However, in most cases one must be satisfied with an analysis of the so-called practical convergence of the successive approximation process. By practical convergence we mean the determination of the percent contribution of each of the computed approximations in a sum of their absolute values, where the sum is arbitrarily taken to be 100%. This gives some indication of what the percent contribution will be for the subsequent approximations in the numerical values of the computed physical and mechanical characteristics. In [22] the stress induced by an axial compression (expansion) of a transversely isotropic solid cylinder of finite length with a circular groove (different groove geometries were considered, such as wavy, triangular, and trapezoidal) was studied and the stress concentration coefficient was determined to the fourth order in a parameter small compared with unity (that is, the first four terms of the series were found). The contribution of the zeroth approximation was about 38-44%, the first was 44-47%, the second 6-13%, and the third 2-3%. All numerical values of these four approximations for three different groove shapes satisfy the inequality $\Delta_{j+1}/\Delta_j < \Delta_j/\Delta_{j-1}$ (j = 1, 2). If it is assumed that the next (fourth) approximation also satisfies this equality (with j = 3) then an upper bound to its contribution in the sum of the five approximations is 0.5-1.2%.

Similar studies of the practical convergence of the method of perturbation of boundary shape have been done in other three-dimensional elastic problems for noncanonical regions [65, 66, 180, 208], in the theory of thin shells with curved apertures [69-71], in the mechanics of composite materials with small-scale structural distortions [8-11, 13, 14], in the theory of emission of sound by noncircular cylindrical shells in a fluid [36], in unsteady problems involving the stress of a gas-saturated massif near a noncircular cylindrical shaft [77, 185, 186], etc.

Note on the Solution of Unsteady Problems in Continuum Mechanics. In solving unsteady boundary-value problems in continuum mechanics for noncanonical regions it is natural to start with the combined application of the method of perturbation of boundary shape and the Laplace transform with respect to time. As mentioned in Sec. 3, this approach was used in [76, 77, 185, 186, 258-260, 286-289] in solving unsteady boundary-value problems involving gas-saturated media with noncanonical cavities. Concerning the effectiveness of this combined approach (method of perturbation of boundary shape and the Laplace transform with respect to time) in unsteady problems in continuum mechanics, we note that, as the order of the approximation increases, the order of the corresponding differential operators also increases, especially with respect to the radial variable. This leads to higher powers of the Laplace transform parameters in the transformed equations. Hence, when the equations are transformed to functions of time, higher negative powers of the time t (or the dimensionless time Fo) will appear. This means that this approach will lead to a convergent iterative process when the region under consideration deviates only slightly from a canonical region, and for relatively large values of the time.

If this restriction is not acceptable (for small values of Fo, for example), then it will be necessary to study the asymptotic behavior of the solution as Fo $\to$ 0 (s $\to \infty$), or to apply (if necessary) various techniques of speeding up the convergence or, if this does not lead to satisfactory results, to develop other approaches which do not involve the combined application of these two methods. The practical convergence of the numerical results for the successive approximations in problems of this kind have been studied in [77, 185, 186].

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