On the derivation of a boundary element method for diffusion convection-reaction problems of compressible flow in exponentially inhomogeneous media

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Abstract. Boundary value problems (BVPs) of anisotropic and exponentially-graded media governed by a diffusion convection-reaction (DCR) equation are considered. The governing equation is of spatially varying coefficients (with an anisotropic diffusion coefficient). The variable coefficients equation is firstly transformed into a constant coefficients equation, from which we derive a boundary integral equation. A boundary element method (BEM) is then constructed to be used for finding numerical solutions to the BVPs. For the computation of the solutions a FORTRAN code is developed. Some examples of problems are solved. The numerical solutions obtained verify the validity of the analysis used to construct the boundary element method with accurate and consistent solutions. The results also show that the BEM procedure elapses very efficient time in producing the solutions. In addition, the results indicate the effect of anisotropy of the media on the solutions.

1. Introduction

By referring to the two-dimensional Cartesian coordinate system $Ox_1x_2$ this paper will concern with the DCR equation of compressible flow

$$
\frac{\partial}{\partial x_i} \left[ d_{ij}(x) \frac{\partial \beta(x)}{\partial x_j} \right] - \frac{\partial}{\partial x_i} [\nu_i(x)\beta(x)] - \rho(x)\beta(x) = 0
$$

(1)

where $i, j = 1, 2$, $x = (x_1, x_2)$, $d_{ij}$ is the anisotropic diffusion or conduction coefficient, $\nu_i$ is the velocity, $\rho$ is the reaction coefficient and $\beta$ is the dependent variable. Within the domain in question $|d_{ij}|$ is a real symmetrical matrix satisfying $d_{11}d_{22} - d_{12}^2 > 0$. For
the repeated indices in equation (1) summation convention applies so that equation (1) can be written explicitly

$$\frac{\partial}{\partial x_1} \left( d_{11} \frac{\partial \beta}{\partial x_1} \right) + \frac{\partial}{\partial x_1} \left( d_{12} \frac{\partial \beta}{\partial x_2} \right) + \frac{\partial}{\partial x_2} \left( d_{12} \frac{\partial \beta}{\partial x_1} \right) + \frac{\partial}{\partial x_2} \left( d_{22} \frac{\partial \beta}{\partial x_2} \right)$$

$$- \frac{\partial}{\partial x_1} (\nu_1 \beta) - \frac{\partial}{\partial x_2} (\nu_2 \beta) - \rho \beta = 0$$

Also, in equation (1) the coefficients $d_{ij}$, $\nu_i$ and $\rho$ vary spatially and continuously which is applicable when the medium is inhomogeneous or is a functionally graded material (FGM).

DCR equation is usually used for modeling heat transfer and mass transport problems. According to Ravnik and Škerget [1], in mass transport which frequently occurs in environments, the convection process takes place with a flow velocity which varies in the medium in question, and in the case of turbulence modeling with turbulent viscosity hypothesis, the diffusivity also changes in the domain. These situations imply the DCR equation (1) becomes relevant.

FGMs are materials possessing characteristics which vary (with time and position) according to a mathematical function. FGMs are mainly artificial materials which are produced to meet a preset practical performance (see for example [2, 3]). Heat transfer in FGMs, for which equation (1) is usually used as the governing equation, is among application that has been considerably studied by many people. This constitutes relevancy of solving equation (1).

A number of papers previously considering DCR equation are [4, 5] in which AL-Bayati and Wrobel solved an isotropic-DCR equation with variable velocity, [6] where AL-Bayati and Wrobel solved an isotropic-DCR equation with a source term, [7] in which Fendoğlu et al. considered a constant coefficients unsteady isotropic-DCR equation with a source term, [8] by Rocca et al. which concerns with an isotropic-DCR equation with variable velocity, [9] in which Samec and Škerget solved an isotropic-DCR equation with variable velocity.

Not so many works have been done on DCR equation of type (1) for anisotropic FGMs where the diffusivity, velocity and reaction coefficients are simultaneously variable. Similar works of anisotropic materials but for different kinds of applications have been done previously in [10, 11, 12, 13] for Helmholtz equation, in [14, 15, 16] for DC equation, in [17, 18, 19, 20] for vector elliptic equation, in [21] for a scalar Laplace type equation, in [22, 23, 24, 25] for a scalar elliptic type equation, and in [26, 27, 28] for a modified Helmholtz type equation.

Numerical solutions $\beta$ and its derivatives $\partial \beta / \partial x_1$, $\partial \beta / \partial x_2$ to (1) in the domain $\Omega$, subjected to the boundary condition that either $\beta$ or

$$P = d_{ij} \left( \partial \beta / \partial x_i \right) n_j$$

is known on the boundary $\partial \Omega$, are sought. The investigation of this paper is strictly mathematical. The purpose is mainly to develop a boundary element method for finding the numerical solutions.
2. Transformation of the variable to a constant coefficients equation

We limit the coefficients $\nu_i$, $d_{ij}$ and $\rho$ to be varying spatially according to a specific continuous function $h(x)$

\begin{align*}
d_{ij}(x) &= \hat{d}_{ij} h(x) \\
\nu_i(x) &= \hat{\nu}_i h(x) \\
\rho(x) &= \hat{\rho} h(x)
\end{align*}

where $\hat{d}_{ij}$, $\hat{\nu}_i$ and $\hat{\rho}$ are constant and the inhomogeneity function $h(x)$ is a differentiable function taking the exponential form

\begin{equation}
h(x) = [A \exp (\alpha_i x_i)]^2
\end{equation}

where $A$ and $\alpha_i$ are constants. So the material under consideration is an exponentially graded material.

Substitution of (3), (4) and (5) into (1) gives

\begin{equation}
\hat{d}_{ij} \frac{\partial}{\partial x_i} \left( h \frac{\partial \beta}{\partial x_j} \right) - \hat{\nu}_i \frac{\partial (h \beta)}{\partial x_i} - \hat{\rho} h \beta = 0
\end{equation}

Write

\begin{equation}
\beta(x) = h^{-1/2} (x) \varsigma(x)
\end{equation}

then equation (7) can be rewritten as

\begin{equation}
\hat{d}_{ij} \frac{\partial}{\partial x_i} \left[ h (h^{-1/2} \varsigma - \hat{\nu}_i \frac{\partial (h^{1/2} \varsigma)}{\partial x_i} - \hat{\rho} h^{1/2} \varsigma \right] = 0
\end{equation}

which can be further written as

\begin{equation}
\hat{d}_{ij} \left[ \left( \frac{1}{4} h^{-3/2} \frac{\partial h}{\partial x_i} \frac{\partial h}{\partial x_j} - \frac{1}{2} h^{-1/2} \frac{\partial^2 h}{\partial x_i \partial x_j} \right) \varsigma + h^{1/2} \frac{\partial^2 \varsigma}{\partial x_i \partial x_j} - h \hat{\nu}_i \frac{\partial (h^{1/2} \varsigma)}{\partial x_i} - \hat{\rho} h^{1/2} \varsigma \right] = 0
\end{equation}

The identities

\begin{align*}
\frac{\partial^2 h^{1/2}}{\partial x_i \partial x_j} &= - \left( \frac{1}{4} h^{-3/2} \frac{\partial h}{\partial x_i} \frac{\partial h}{\partial x_j} - \frac{1}{2} h^{-1/2} \frac{\partial^2 h}{\partial x_i \partial x_j} \right) \\
\frac{\partial (h^{1/2} \varsigma)}{\partial x_i} &= h^{1/2} \frac{\partial \varsigma}{\partial x_i} + \varsigma \frac{\partial h^{1/2}}{\partial x_i}
\end{align*}

allow equation (9) to be written in the form

\begin{equation}
h^{1/2} \left( \hat{d}_{ij} \frac{\partial^2 \varsigma}{\partial x_i \partial x_j} - \hat{\nu}_i \frac{\partial \varsigma}{\partial x_i} \right) - \varsigma \left( \hat{d}_{ij} \frac{\partial^2 h^{1/2}}{\partial x_i \partial x_j} + \hat{\nu}_i \frac{\partial h^{1/2}}{\partial x_i} \right) - \hat{\rho} h^{1/2} \varsigma = 0
\end{equation}

So that if $h$ in (10) satisfies

\begin{equation}
\hat{d}_{ij} \frac{\partial^2 h^{1/2}}{\partial x_i \partial x_j} + \hat{\nu}_i \frac{\partial h^{1/2}}{\partial x_i} = 0
\end{equation}
then the transformation (8) brings the variable coefficients equation (1) into a constant coefficients equation
\[ \hat{d}_{ij} \frac{\partial^2 \varsigma}{\partial x_i \partial x_j} - \hat{\nu}_i \frac{\partial \varsigma}{\partial x_i} - \hat{\rho} \varsigma = 0 \] (12)

Or if \( h \) in (10) satisfies
\[ \hat{d}_{ij} \frac{\partial^2 h^{1/2}}{\partial x_i \partial x_j} + \hat{\nu}_i \frac{\partial h^{1/2}}{\partial x_i} + \hat{\rho} h^{1/2} = 0 \] (13)
then
\[ \hat{d}_{ij} \frac{\partial^2 \varsigma}{\partial x_i \partial x_j} - \hat{\nu}_i \frac{\partial \varsigma}{\partial x_i} = 0 \] (14)

The exponential function \( h(x) \) in (6) will satisfy (11) and (13) respectively when
\[ \hat{d}_{ij} \alpha_i \alpha_j + \hat{\nu}_i \alpha_i = 0 \] (15)
\[ \hat{d}_{ij} \alpha_i \alpha_j + \hat{\nu}_i \alpha_i + \hat{\rho} = 0 \] (16)

Furthermore use of (3) and (8) in (2) yields
\[ P = -P_h \varsigma + P_\varsigma h^{1/2} \] (17)

where \( P_h (x) = \hat{d}_{ij} (\partial h^{1/2}/\partial x_j) n_i \) and \( P_\varsigma (x) = \hat{d}_{ij} (\partial \varsigma/\partial x_j) n_i \).

3. The integral equation

By using Gauss divergence theorem, equations (12) and (14) can be transformed into a boundary integral equation
\[ \kappa(\chi) \varsigma(\chi) = \int_{\partial \Omega} \{ P_\varsigma(x) \Lambda(x, \chi) - [P_\nu(x) \Lambda(x, \chi) + \Theta(x, \chi)] \varsigma(x) \} ds(x) \] (18)

where \( P_\nu(x) = \hat{\nu}_i n_i(x) \) and \( \chi = (\chi_1, \chi_2) \), \( \kappa = 0 \) if \( (\chi_1, \chi_2) \notin \Omega \cup \partial \Omega \), \( \kappa = 1 \) if \( (\chi_1, \chi_2) \) lies inside the domain \( \Omega \), \( \kappa = \frac{1}{2} \) if \( (\chi_1, \chi_2) \) is on the boundary \( \partial \Omega \) given that \( \partial \Omega \) has a continuously turning tangent at \( (\chi_1, \chi_2) \). In (18) the fundamental solution \( \Lambda(x, \chi) \) for equations (12) and (14) respectively satisfies
\[ \hat{d}_{ij} \frac{\partial^2 \Lambda(x, \chi)}{\partial x_i \partial x_j} + \hat{\nu}_i \frac{\partial \Lambda(x, \chi)}{\partial x_i} - \hat{\rho} \Lambda(x, \chi) = -\delta(x - \chi) \] (19)
\[ \hat{d}_{ij} \frac{\partial^2 \Lambda(x, \chi)}{\partial x_i \partial x_j} + \hat{\nu}_i \frac{\partial \Lambda(x, \chi)}{\partial x_i} = -\delta(x - \chi) \] (20)

and \( \Theta(x, \chi) \) satisfies
\[ \Theta(x, \chi) = \hat{d}_{ij} \frac{\partial \Lambda(x, \chi)}{\partial x_j} n_i \]
where $\delta$ is the Dirac delta function. For 2-D problems the function $\Lambda$ for (19) and (20) is respectively given as (see Azis [29])

$$\Lambda(x, \chi) = \frac{\bar{\tau}}{2\pi D} \exp \left( -\frac{\nu}{2D} \right) K_0 (\mu_1 R)$$

$$\Lambda(x, \chi) = \frac{\bar{\tau}}{2\pi D} \exp \left( -\frac{\nu}{2D} \right) K_0 (\mu_2 R)$$

where $\mu_1 = \sqrt{\left(\nu/2D\right)^2 + (\bar{\rho}/D)}$, $\mu_2 = \sqrt{\left(\nu/2D\right)^2}$, $D = [\hat{d}_{11} + 2\hat{d}_{12} \tau + \hat{d}_{22} (\tau^2 + \nu^2)]/2$, $R = \hat{x} - \hat{x}$, $\hat{x} = (x_1 + \tau x_2, \tau x_2)$, $\hat{\chi} = (\chi_1 + \tau \chi_2, \tau \chi_2)$, $\nu = (\bar{\nu}_1 + \tau \bar{\nu}_2, \bar{\nu}_2)$, $\hat{R} = \sqrt{(x_1 + \tau x_2 - \chi_1 - \tau \chi_2)^2 + (\tau x_2 - \tau \chi_2)^2}$, and $\nu = \sqrt{(\nu_1 + \tau \nu_2)^2 + (\tau \nu_2)^2}$ where $\tau$ and $\tau$ are respectively the real and the positive imaginary parts of the complex root $\tau$ of the quadratic equation $d_{11} + 2d_{12} \tau + d_{22} \tau^2 = 0$ and $K_0$ is the modified Bessel function. Use of (8) and (17) in (18) yields

$$\kappa h^{1/2} \beta = \int_{\partial l} \left\{ \left( h^{-1/2} \Lambda \right) P + \left[ \left( P_h - P_v h^{1/2} \right) \Lambda - h^{1/2} \Theta \right] \beta \right\} ds \quad (21)$$

4. Discretisation

Divide the boundary $\partial \Omega$ into $L$ segments $\partial \Omega_l \equiv [q_{l-1}, q_l]$ for $l = 1, 2, 3, \ldots, L$ where $q_{l-1}$ and $q_l$ are the endpoints of the segment $\partial \Omega_l$. It is assumed that $\beta$ and $P$ are constant along each boundary segment $\partial \Omega_l$ taking on their values at the mid point $q_l = (q_{l-1} + q_l)/2$. Then the discretised form of (21) may be written as

$$\kappa(\chi) h^{1/2}(\chi) \beta(\chi) = \sum_{l=1}^{L} \left\{ P(q_l) \int_{q_{l-1}}^{q_l} [h^{-1/2}(x) \Lambda(x, \chi)] ds(x) + \beta(q_l) \int_{q_{l-1}}^{q_l} \left\{ [P_h(x) - P_v(x) h^{1/2}(x)] \Lambda(x, \chi) - h^{1/2}(x) \Theta(x, \chi) \right\} ds(x) \right\}$$

The integral equation (22) is used to find the boundary unknowns $\beta(x)$ or $P(x)$ on $\partial \Omega$. Then the solutions $\beta(x)$ and its derivatives in the domain $\Omega$ are evaluated using the complete boundary data $\beta(x)$ and $P(x)$ on $\partial \Omega$.

If the source point $\chi$ lies on the boundary $\partial \Omega$ (thus $\eta(\chi) = \frac{1}{2}$), say $\chi$ lies on the boundary segment $\partial \Omega_k$ ($k = 1, 2, \ldots, L$) so that $\chi$ is the mid-point $\chi_k$ of $\partial \Omega_k$, then equation (22) can be written as

$$\frac{1}{2} h^{1/2}(\chi_k) \beta(\chi_k) = \sum_{l=1}^{L} \left\{ P(q_l) \int_{q_{l-1}}^{q_l} [h^{-1/2}(x) \Lambda(x, \chi_k)] ds(x) + \beta(q_l) \int_{q_{l-1}}^{q_l} \left\{ [P_h(x) - P_v(x) h^{1/2}(x)] \Lambda(x, \chi_k) - h^{1/2}(x) \Theta(x, \chi_k) \right\} ds(x) \right\}$$
for $k = 1, 2, \ldots, L$. This equation may be written in matrix form

$$\frac{1}{2} h^{1/2}_k \beta_k - \sum_{l=1}^{L} \hat{H}_{kl} \beta_l = \sum_{l=1}^{L} G_{kl} P_l$$

(23)

where $h^{1/2}_k = h^{1/2}(\hat{q}_k)$, $\beta_k = \beta(\hat{q}_k)$, $P_l = P(\hat{q}_l)$, and

$$\hat{H}_{kl} = \int_{q_{k-1}}^{q_k} \left\{ \left[ P_h(x) - P_{v}(x) h^{1/2}(x) \right] \Lambda(x, \hat{q}_k) - h^{1/2}(x) \Theta(x, \hat{q}_k) \right\} ds(x)$$

(24)

$$G_{kl} = \int_{q_{k-1}}^{q_k} \left[ h^{-1/2}(x) \Lambda(x, \hat{q}_k) \right] ds(x)$$

(25)

The integrals in equations (24) and (25) can be evaluated numerically. And also the values of the modified Bessel function involved in the fundamental solutions $\Lambda$ and $\Theta$ can be approached by their polynomial approximations (see Abramowitz and Stegun [30]). In a simpler way, equation (23) may be written as

$$\sum_{l=1}^{L} H_{kl} \beta_l = \sum_{l=1}^{L} G_{kl} P_l$$

(26)

where

$$H_{kl} = \begin{cases} 
-\hat{H}_{kl} & \text{when } k \neq l \\
\frac{1}{2} h^{1/2}_k - \hat{H}_{kl} & \text{when } k = l 
\end{cases}$$

Equation (26) can be rearranged by putting the unknowns on the left hand side and all the knowns on the right hand side to obtain a $L \times L$ linear system of algebraic equations in the form

$$AX = B$$

(27)

where $X$ is the unknown matrix.

Once the unknowns $\beta$ and $P$ on the boundary $\partial \Omega$ are obtained from the equation (27), we can calculate the value of $\beta$ at any point $\chi$ inside the domain $\Omega$ by using the following equation

$$\beta(\chi) = h^{-1/2}(\chi) \sum_{l=1}^{L} \left\{ P(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left[ h^{-1/2}(x) \Lambda(x, \chi) \right] ds(x) \right\} + \beta(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left\{ \left[ P_h(x) - P_{v}(x) h^{1/2}(x) \right] \Lambda(x, \chi) - h^{1/2}(x) \Theta(x, \chi) \right\} ds(x)$$

We can also calculate the values of the derivatives $\partial \beta/\partial \chi_1$ and $\partial \beta/\partial \chi_2$ using the
following equations

\[
\frac{\partial \beta}{\partial \chi_1}(\chi) = h^{-1/2}(\chi) \left\{ \sum_{l=1}^{L} \left\{ P(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left[ h^{-1/2}(x) \frac{\partial \Lambda(x, \chi)}{\partial \chi_1} \right] ds(x) \right. \right.
\]

\[
+ \beta(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left[ \left[ P_h(x) - P_\nu(x) h^{1/2}(x) \right] \frac{\partial \Lambda(x, \chi)}{\partial \chi_1} \right. \right.
\]

\[
- h^{1/2}(x) \frac{\partial \Theta(x, \chi)}{\partial \chi_1} ds(x) \left. \right\} - \beta(\chi) \frac{\partial h^{1/2}(\chi)}{\partial \chi_1} \}
\]

\[
\frac{\partial \beta}{\partial \chi_2}(\chi) = h^{-1/2}(\chi) \left\{ \sum_{l=1}^{L} \left\{ P(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left[ h^{-1/2}(x) \frac{\partial \Lambda(x, \chi)}{\partial \chi_2} \right] ds(x) \right. \right.
\]

\[
+ \beta(\hat{q}_l) \int_{q_{l-1}}^{q_l} \left[ \left[ P_h(x) - P_\nu(x) h^{1/2}(x) \right] \frac{\partial \Lambda(x, \chi)}{\partial \chi_2} \right. \right.
\]

\[
- h^{1/2}(x) \frac{\partial \Theta(x, \chi)}{\partial \chi_2} ds(x) \left. \right\} - \beta(\chi) \frac{\partial h^{1/2}(\chi)}{\partial \chi_2} \}
\]

5. Numerical examples

The aim of this section is to justify the analysis used to derive the boundary integral equation (21). Some problems will be considered in which the function \( h \) is assumed to take the multi parameter exponential form (6). Solutions to the problems are calculated using a FORTRAN script and a specific command is embedded inside the script to count the elapsed CPU computation time for obtaining the results as to show the efficiency of the BEM. The other aspects that will be justified are the accuracy and consistency of the BEM solutions as to see whether or not the developed FORTRAN script works correctly. Moreover, we will also study the influence of the anisotropy and inhomogeneity of the material under consideration on the solutions.

5.1. Test problems

The domain and the boundary conditions are as depicted in Figure 1.

5.1.1. Problem 1: The function \( h \) is assumed to satisfy equation (11). And the parameters \( \alpha_i \) are required to satisfy (15). The constant coefficients are

\[
\hat{d}_{ij} = \begin{bmatrix} 1.15 & 0.15 \\ 0.15 & 1 \end{bmatrix} \quad \hat{\nu}_i = (0.15, 0.25) \quad \hat{\rho} = 0.15
\]

The inhomogeneity function \( h \) is taken to be

\[
h(x) = [2 \exp (0.05x_1 - 0.217242x_2)]^2
\]
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Figure 1. The domain Ω

Figure 2. The absolute errors of β (left), ∂β/∂x₁ (center), ∂β/∂x₂ (right) solutions for Problem 1

The exact solution is

$$\beta(x) = 0.5 \exp (0.1x_1 - 0.076656x_2)$$

Figures 2 and 3 show the accuracy and consistency (between the scattering and flow) of the numerical solutions when a number of 320 boundary segments of equal length, namely 80 segments on each side, are used. Efficiency of the BEM is indicated by a short elapsed CPU time which is only in 189.1875 seconds for obtaining solutions β(x) and its derivatives at 19×19 interior points.

5.1.2. Problem 2: The function h is assumed to satisfy equation (13). And the parameters αᵢ are required to satisfy (16). The constant coefficients are

$$\hat{d}_{ij} = \begin{bmatrix} 1.15 & 0.15 \\ 0.15 & 1 \end{bmatrix} \quad \hat{\nu} = (0.15, 0.25) \quad \hat{\rho} = -0.15$$

The inhomogeneity function h is taken to be

$$h(x) = [4 \exp (0.05x_1 - 0.528961x_2)]^2$$
The exact solution is

\[
\beta(\mathbf{x}) = 0.25 \exp (0.1x_1 + 0.547014x_2)
\]

Figures 4 and 5 show the accuracy and consistency (between the scattering and flow) of the numerical solutions when a number of 320 boundary segments of equal length, namely 80 segments on each side, are used. Efficiency of the BEM is indicated by a short elapsed CPU time which is only in 188.4375 seconds for obtaining solutions \(\beta(\mathbf{x})\) and its derivatives at 19×19 interior points.

5.2. Problems without any simple exact solutions
A layered material consisting of eight layers of the same size and with boundary conditions as depicted in Figure 6 is under consideration. Each layer is supposed to
be homogeneous, but from layer to layer the diffusion $d_{ij}$, velocity $\nu_i$ and reaction $\rho$ coefficients are assumed to be varying as smoothly as the variability can be fitted to a exponential function $h(x) = [A \exp (\alpha_i x_i)]^2$.

Figure 6. A layered material as the domain $\Omega$

Just as an illustration, suppose that we have a set of data of the diffusion $d_{ij}$, velocity $\nu_i$ and reaction $\rho$ coefficient values at center point of each layer as shown in Table 1. And we also have reference values of constant coefficients

$$d_{ij} = \begin{bmatrix} 1.3 & 0 \\ 0 & 1.5 \end{bmatrix} \quad \nu_i = (0.2, 0.5) \quad \rho = -0.25$$

Fitting the data in Table 1 to the function $h(x) = [\exp (\alpha_1 x_1 + \alpha_2 x_2)]^2$ we will get the values of the parameters $\alpha_1$ and $\alpha_2$

$$\alpha_1 = 0 \quad \alpha_2 = -0.607625$$

Table 1. Example of the diffusion $d_{ij}$, velocity $\nu_i$ and reaction $\rho$ coefficient data

| Layer | $d_{11}$ | $d_{12}$ | $d_{22}$ | $\nu_1$ | $\nu_2$ | $\rho$ |
|-------|----------|----------|----------|---------|---------|-------|
| 1     | 1.20492  | 0        | 1.39029  | 0.18537 | 0.46343 | -0.23171 |
| 2     | 1.03511  | 0        | 1.19435  | 0.15925 | 0.39812 | -0.19906 |
| 3     | 0.88923  | 0        | 1.02603  | 0.13680 | 0.34201 | -0.17101 |
| 4     | 0.76391  | 0        | 0.88143  | 0.11752 | 0.29381 | -0.14691 |
| 5     | 0.65625  | 0        | 0.75721  | 0.10096 | 0.25240 | -0.12620 |
| 6     | 0.56376  | 0        | 0.65050  | 0.08673 | 0.21683 | -0.10842 |
| 7     | 0.48431  | 0        | 0.55882  | 0.07451 | 0.18627 | -0.09314 |
| 8     | 0.41606  | 0        | 0.48007  | 0.06401 | 0.16002 | -0.08001 |
Therefore we can then approximate the layered material as a sole material with continuously varying coefficients. So we may use the analysis in Sections 2 – 4 to solve the problem.

Again, a number of 320 segments of equal length are used. As shown in Figure 7 for the constant orthotropic diffusion coefficient \( \hat{d}_{ij} \) given above the solution \( \beta \) exhibits the nature of the considered medium as a layered material.

However, if we assume that the material under consideration is a sole material varying continuously with constant coefficients and inhomogeneity function

\[
\hat{d}_{ij} = \begin{bmatrix} 1.3 & 1 \\ 1 & 1.5 \end{bmatrix}, \quad \hat{\nu}_i = (0.2, 0.5), \quad \hat{\rho} = -0.25
\]

\[
h(x) = \left[ \exp \left( -0.607625x_2 \right) \right]^2
\]

then we will obtain different solutions \( \beta \) as shown in Figure 8. This means that the anisotropy of the medium gives an impact on the solution. Therefore in application it is necessary for the anisotropy to be taken into account.

6. Conclusion
A standard BEM has been used to find numerical solutions to boundary value problems governed by the anisotropic diffusion-convection-reaction equation (1) of compressible
flow with spatially variable coefficients for exponentially graded (inhomogeneous) media. The BEM gives accurate and consistent solutions and uses very efficient computation time for producing the results, which verifies that the analysis for deriving the boundary integral equation in Section 3 is valid and the developed FORTRAN code works well. Moreover, effect of the anisotropy and inhomogeneity of the media on the solutions are also presented.

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