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Green's functions for infinite planes and half-planes consisting of quasicrystal bi-materials*

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Abstract: This paper deals with the combination of point phonon and phason forces applied in the interior of infinite planes and half-planes of 1D quasicrystal bi-materials. Based on the general solution of quasicrystals, a series of displacement functions are adopted to obtain Green's functions for infinite planes and bi-material planes composed of two half-planes in the closed form, when the two half-planes are supposed to be ideally bonded or to be in smooth contact. Since the physical quantities can be readily calculated without the need of performing any transform operations, Green's functions are very convenient to be used in the study of point defects and inhomogeneities in the quasicrystal materials.

Key words: Green's functions, 1D quasicrystal, Infinite planes, Half-planes, Bi-materials
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1 Introduction

Quasicrystals (QCs) were discovered around 1984 (Shechtman *et al*., 1984). The discovery was a significant breakthrough for condensed matter physics. The electronic structure and the optic, magnetic, thermal, and mechanical properties of the material have been extensively investigated in experimental and theoretical analyses (Socolar *et al*., 1986; Ronchetti, 1987; Wollgarten *et al*., 1993). These investigations have revealed the material's complex structure and unusual properties. Elasticity is one of the interesting properties of QCs. In particular, the field of linear elastic theory of QCs has received considerable interest (Ding *et al*., 1993; Wang *et al*., 1997). For reviews see (Hu *et al*., 2000; Fan and Mai, 2004).

The elastic body, joined with two dissimilar materials with point forces applied at an arbitrary point, is fundamental to the development of elastic theory and is of vital significance in the structural design. For elastic materials, Huang and Wang (1991) and Ting (1996) conducted systematic studies on Green's functions for point forces applied in the interior of a two-phase infinite space. With regard to piezoelectric materials, Ding *et al*. (1997a) presented the closed-form point force and point charge solutions for a two-phase piezoelectric medium, and considered the plane problems in a similar way (Ding *et al*., 1997b). However, relevant Green's functions for 1D QCs have not been attempted. The purpose of this paper is to study the plane problems of point forces applied in the interior of an infinite bi-material QC.

For a 1D QC referred to a Cartesian coordinate system (x_1, x_2, x_3), let x_1-x_2 plane be the periodic plane and x_3 be the quasi-periodic direction. In the absence of body forces, the general equations governing plane problems of 1D orthorhombic QCs can be written as (Wang *et al*., 1997)

$$\varepsilon_{mn} = \frac{\partial_n u_m + \partial_m u_n}{2}, \quad w_{3n} = \partial_n w_3, \tag{1}$$

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$$\partial_n\sigma_{mn}=0,\ \ \partial_n H_{3n}=0, \tag{2}$$

$$\begin{aligned}
&\sigma_{11}=C_{11}\varepsilon_{11}+C_{13}\varepsilon_{33}+R_1w_{33},\\
&\sigma_{33}=C_{13}\varepsilon_{11}+C_{33}\varepsilon_{33}+R_3w_{33},\\
&\sigma_{31}=\sigma_{13}=2C_{55}\varepsilon_{31}+R_6w_{31},\\
&H_{33}=R_1\varepsilon_{11}+R_3\varepsilon_{33}+K_3w_{33},\\
&H_{31}=2R_6\varepsilon_{31}+K_1w_{31},
\end{aligned} \tag{3}$$

where m, n=1, 3; σ_{mn} and ε_{mn} are phonon stress and strain, respectively; H_{3n} and w_{3n} stand for phason stress and strain, respectively; C_{pq} and K_p are elastic constants in the phonon and phason fields, respectively; and R_p is phonon-phason coupling elastic constant.

It is clear that the structures of the governing equations of 1D QCs are analogous to those of piezoelectric materials, with slight difference in their coefficients. Therefore, the methods developed for transversely isotropic piezoelectric materials (Ding *et al*., 1996) were directly applied to establish general solutions of 1D hexagonal QCs (Chen *et al*., 2004). In addition, the 3D fundamental solutions of an infinite 1D QC space subject to point loads have been derived based on the general solution. In virtue of the analysis technique of QCs (Gao and Zhao, 2006), the general solution of 1D orthorhombic QCs for plane problems takes the form (Gao *et al*., 2008):

$$u_1=\delta_{Ii}\partial_1\psi_i,\ \ U_\alpha=k_{\alpha i}\partial_3\psi_i, \tag{4}$$

where δ_{ij} is the Kronecker delta symbol and the following summation conventions are used in this study: the Einstein summation over repeated lower case indices from 1 to 3 is applied, while upper case indices take on the same numbers as the corresponding lower case ones, but are not summed. For compactness, the notations $U_1=u_3$, $U_2=w_3$, $T_{11}=\sigma_{33}$, $T_{21}=H_{33}$, $T_{12}=\sigma_{31}$, and $T_{22}=H_{31}$ are employed in this study. In addition, the potential function ψ_i satisfies:

$$\nabla_I^2\psi_i=\partial_1^2\psi_i+\partial_3^2\psi_i/s_I^2=0. \tag{5}$$

The values of k_{1i}, k_{2i}, and s_i^2 are related by

$$\begin{aligned}
&\frac{C_{55}+(C_{13}+C_{55})k_{1i}+(R_1+R_6)k_{2i}}{C_{11}}\\
&=\frac{C_{33}k_{1i}+R_3k_{2i}}{C_{13}+C_{55}+C_{55}k_{1i}+R_6k_{2i}}\\
&=\frac{R_3k_{1i}+K_3k_{2i}}{R_1+R_6+R_6k_{1i}+K_1k_{2i}}=\frac{1}{s_i^2}.
\end{aligned} \tag{6}$$

The components of stresses obtained from Eqs. (1), (3) and (4) can be shown as

$$\sigma_{11}=m_{1i}s_I^2\partial_1^2\psi_i,\ T_{\alpha 1}=-m_{\alpha i}\partial_1^2\psi_i,\ T_{\alpha 2}=m_{\alpha i}\partial_1\partial_3\psi_i, \tag{7}$$

where $m_{1i}=C_{55}(1+k_{1i})+R_6k_{2i}$, $m_{2i}=R_6(1+k_{1i})+K_1k_{2i}$.

For brevity and conciseness, in the following two sections, Green's functions for infinite planes and infinite bi-material planes will be given only for the case of distinct eigenvalues.

2 Green's functions for infinite planes

Consider the problem of a 1D QC plane subject to a point phonon force F in the x_1-direction, point phonon and phason forces P_α in the x_3-direction applied simultaneously at an arbitrary point in the plane. For convenience, we take this point as the origin of Cartesian coordinates. The problem can be divided into two sub-problems: the problem of point phonon force F in the x_1-direction and the problem of point phonon and phason forces P_α in the x_3-direction.

2.1 Point force F in the x_1-direction

This is a plane problem, it can be assumed that

$$\psi_i=A_i\left(x_1\ln r_I+s_Ix_3\arctan\frac{x_1}{s_Ix_3}-x_1\right), \tag{8}$$

where $r_i=\sqrt{x_1^2+s_i^2x_3^2}$, and A_i is undetermined constant. Substitution of Eq. (8) into Eqs. (4) and (7) yields the expressions for the phonon and phason fields as follows:

$$u_1=A_i\ln r_i,\ \ U_\alpha=k_{\alpha i}A_is_I\arctan\frac{x_1}{s_Ix_3}, \tag{9}$$

$$\sigma_{11}=m_{1i}A_i\frac{s_I^2x_1}{r_I^2},\ T_{\alpha 1}=-m_{\alpha i}A_i\frac{x_1}{r_I^2},\ T_{\alpha 2}=m_{\alpha i}A_i\frac{s_I^2x_3}{r_I^2}. \tag{10}$$

The continuity of the components U_α across the line x_3=0 requires that

$$k_{\alpha i}A_i s_I = 0. \tag{11}$$

Further, consider the equilibrium conditions of a strip between two lines $x_3=\pm h$, yielding:

$$\int_{-\infty}^{+\infty}\left[T_{12}(x_1,h)-T_{12}(x_1,-h)\right]\mathrm{d}x_1 + F = 0. \tag{12}$$

Substituting Eq. (10) into Eq. (12), we can obtain

$$2\pi m_{1i}A_i s_I + F = 0. \tag{13}$$

Thus, the unknown constant A_i can be solved from Eqs. (11) and (13):

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = -\frac{F}{2\pi}\begin{bmatrix} k_{11}s_1 & k_{12}s_2 & k_{13}s_3 \\ k_{21}s_1 & k_{22}s_2 & k_{23}s_3 \\ m_{11}s_1 & m_{12}s_2 & m_{13}s_3 \end{bmatrix}^{-1}\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}. \tag{14}$$

2.2 Point force P_α in the x_3-direction

We assume the function ψ_i is in the following form:

$$\psi_i = B_i\left(s_I x_3 \ln r_I - x_1 \arctan\frac{x_1}{s_I x_3} - s_I x_3\right), \tag{15}$$

where B_i is a constant to be determined.

Similarly, the expressions for the phonon and phason fields are summarized as follows:

$$u_1 = -B_i \arctan\frac{x_1}{s_i x_3},\ \ U_\alpha = k_{\alpha i}B_i s_I \ln r_I, \tag{16}$$

$$\sigma_{11} = -m_{1i}B_i\frac{s_I^3 x_3}{r_I^2},\ \ T_{\alpha 1} = m_{\alpha i}B_i\frac{s_I x_3}{r_I^2},\ \ T_{\alpha 2} = m_{\alpha i}B_i\frac{s_I x_1}{r_I^2}. \tag{17}$$

The continuity condition of u_1 on x_3=0 demands that

$$\delta_{1i}B_i = 0. \tag{18}$$

Also, the equilibrium condition of the strip bounded by $x_3=\pm h$ becomes:

$$\int_{-\infty}^{+\infty}\left[T_{\alpha 1}(x_1,h)-T_{\alpha 1}(x_1,-h)\right]\mathrm{d}x_1 + P_\alpha = 0. \tag{19}$$

Substituting the expression for $T_{\alpha 1}$ in Eq. (17) into Eq. (19), we can obtain

$$2\pi m_{\alpha i}B_i + P_\alpha = 0. \tag{20}$$

Then the unknown constant B_i can be solved from Eqs. (18) and (20) as follows:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = -\frac{1}{2\pi}\begin{bmatrix} 1 & 1 & 1 \\ m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix}^{-1}\begin{bmatrix} 0 \\ P_1 \\ P_2 \end{bmatrix}. \tag{21}$$

3 Green's functions for infinite planes composed of two half-planes

Consider an infinite plane composed of two QC half-planes with different material constants. Let the lower half-plane $x_3\geq 0$ be occupied by material 1 and the upper half-plane $x_3\leq 0$ be occupied by material 2. The point force is acting at the point (0, h). If the two half-planes are rigidly bonded together along x_3=0, we have the following boundary conditions:

$$u_1^- = u_1^+,\ \ U_\alpha^- = U_\alpha^+,\ \ T_{\alpha 1}^- = T_{\alpha 1}^+,\ \ T_{12}^- = T_{12}^+, \tag{22}$$

where superscripts $^-$ and $^+$ denote the variables in $x_3\geq 0$ and $x_3\leq 0$, respectively. If the half-planes are in smooth contact, i.e., in a complete contact without friction, then

$$U_\alpha^- = U_\alpha^+,\ \ T_{\alpha 1}^- = T_{\alpha 1}^+,\ \ T_{12}^- = 0,\ \ T_{12}^+ = 0. \tag{23}$$

The components of displacements in $x_3\geq 0$ can be decomposed into two parts:

$$u_1^- = u_1 + u_1',\ \ U_\alpha^- = U_\alpha + U_\alpha', \tag{24}$$

where u_1 and U_α are the displacements due to Green's functions for infinite planes, and $U'_{\alpha\beta}$ and u'_3 are the displacements which make Eq. (24) satisfy Eq. (22) or (23). u_1 and U_α can be obtained simply by replacing x_3 by x_3-h in Eqs. (9), (10), (16) and (17).

3.1 Point force *F* applied in the interior of bi-material QC planes

For the case of the lower half-plane, we assume that

$$\psi_i^- = A_i\left[x_1\ln\bar{r}_I + (s_I^- x_3 - s_I^- h)\arctan\frac{x_1}{s_I^- x_3 - s_I^- h} - x_1\right] + A_{ij}^-\left[x_1\ln r_{Ij}^- + (s_I^- x_3 + s_j^- h)\arctan\frac{x_1}{s_I^- x_3 + s_j^- h} - x_1\right], \quad (25)$$

where $\bar{r}_i = \sqrt{x_1^2 + (s_i^- x_3 - s_i^- h)^2}$, $r_{ij}^- = \sqrt{x_1^2 + (s_i^- x_3 + s_j^- h)^2}$. A_i has been obtained in Eq. (14), and A_{ij}^- are nine constants to be determined. Substituting Eq. (25) into Eqs. (4) and (7), we obtain

$$u_1^- = A_i\ln\bar{r}_i + A_{ij}^-\ln r_{ij}^-,$$
$$U_\alpha^- = k_{\alpha i}^-\left(A_i s_I^- \arctan\frac{x_1}{s_I^- x_3 - s_I^- h} + A_{ij}^- s_I^- \arctan\frac{x_1}{s_I^- x_3 + s_j^- h}\right), \quad (26)$$

$$\sigma_{11}^- = m_{1i}^-(s_I^-)^2\left[A_i\frac{x_1}{\bar{r}_I^2} + A_{ij}^-\frac{x_1}{(r_{Ij}^-)^2}\right],$$
$$T_{\alpha 1}^- = -m_{\alpha i}^-\left[A_i\frac{x_1}{\bar{r}_I^2} + A_{ij}^-\frac{x_1}{(r_{Ij}^-)^2}\right], \quad (27)$$
$$T_{\alpha 2}^- = m_{\alpha i}^-\left[A_i\frac{s_I^-(s_I^- x_3 - s_I^- h)}{\bar{r}_I^2} + A_{ij}^-\frac{s_I^-(s_I^- x_3 + s_j^- h)}{(r_{Ij}^-)^2}\right].$$

For the case of the upper half-plane, ψ_i^+ takes the form:

$$\psi_i^+ = A_{ij}^+\left[x_1\ln r_{Ij}^+ + (s_I^+ x_3 - s_j^- h)\arctan\frac{x_1}{s_I^+ x_3 - s_J^- h} - x_1\right], \quad (28)$$

where $r_{ij}^+ = \sqrt{x_1^2 + (s_i^+ x_3 - s_j^- h)^2}$. A_{ij}^+ are also nine undetermined constants. Using Eqs. (4), (7) and (28), one obtains:

$$u_1^+ = A_{ij}^+\ln r_{ij}^+,\ U_\alpha^- = k_{\alpha i}^+ A_{ij}^+ s_I^+ \arctan\frac{x_1}{s_I^+ x_3 - s_j^- h}, \quad (29)$$

$$\sigma_{11}^- = m_{1i}^+(s_I^+)^2 A_{ij}^+\frac{x_1}{(r_{Ij}^+)^2},$$
$$T_{\alpha 1}^+ = -m_{\alpha i}^+ A_{ij}^+\frac{x_1}{(r_{Ij}^+)^2}, \quad (30)$$
$$T_{\alpha 2}^+ = m_{\alpha i}^+ A_{ij}^-\frac{s_I^+(s_I^+ x_3 - s_j^- h)}{(r_{Ij}^+)^2}.$$

The undetermined constants can be obtained using the contact conditions on x_3=0. When the two half-planes are ideally bonded, the conditions in Eq. (22) lead to:

$$A_j + \delta_{Ii}A_{ij}^- = \delta_{Ii}A_{ij}^+,$$
$$k_{\alpha J}^- s_J^- A_j - k_{\alpha i}^- s_I^- A_{ij}^- = k_{\alpha i}^+ s_I^+ A_{ij}^+,$$
$$m_{\alpha J}^- A_j + m_{\alpha i}^- A_{ij}^- = m_{\alpha i}^+ A_{ij}^+, \quad (31)$$
$$m_{1J}^- s_J^- A_j - m_{1i}^- s_I^- A_{ij}^- = m_{1i}^+ s_I^+ A_{ij}^+.$$

When the two half-planes are in smooth contact as defined by Eq. (23), we obtain

$$k_{\alpha J}^- s_J^- A_j - k_{\alpha i}^- s_I^- A_{ij}^- = k_{\alpha i}^+ s_I^+ A_{ij}^+,$$
$$m_{\alpha J}^- A_j + m_{\alpha i}^- A_{ij}^- = m_{\alpha i}^+ A_{ij}^+, \quad (32)$$
$$m_{1J}^- s_J^- A_j - m_{1i}^- s_I^- A_{ij}^- = 0,$$
$$m_{1i}^+ s_I^+ A_{ij}^+ = 0.$$

It can be seen that there are 18 independent linear algebraic equations involved in Eq. (31) or (32), from which the 18 unknown constants A_{ij}^- and A_{ij}^+ can be uniquely determined.

3.2 Point force P_α applied in the interior of bi-material QC planes

For material 1 in x_3≥0, we take ψ_i^- as

$$\psi_i^- = B_i\left[(s_I^- x_3 - s_I^- h)\ln\bar{r}_I - x_1\arctan\frac{x_1}{s_I^- x_3 - s_I^- h} - (s_I^- x_3 - s_I^- h)\right] + B_{ij}^-\left[(s_I^- x_3 + s_J^- h)\ln r_{Ij}^- - x_1\arctan\frac{x_1}{s_I^- x_3 + s_j^- h} - (s_I^- x_3 + s_j^- h)\right], \quad (33)$$

where B_{ij}^- are nine undetermined constants, yet B_i has been obtained in Eq. (21). Substitution of Eq. (33) into Eqs. (4) and (7) leads to:

$$u_1^- = -B_i \arctan\frac{x_1}{s_i^- x_3 - s_i^- h} - B_{ij}^- \arctan\frac{x_1}{s_i^- x_3 + s_j^- h},$$
$$U_\alpha^- = k_{\alpha i}^- (B_i s_I^- \ln \overline{r}_I + B_{ij}^- s_I^- \ln r_{Ij}^-), \quad (34)$$

$$\sigma_{11}^- = -m_{1i}^- (s_I^-)^2 \left[B_i \frac{s_I^- x_3 - s_I^- h}{\overline{r}_I^2} + B_{ij}^- \frac{s_I^- x_3 + s_j^- h}{(r_{Ij}^-)^2} \right],$$
$$T_{\alpha 1}^- = m_{\alpha i}^- \left[B_i \frac{s_I^- x_3 - s_I^- h}{\overline{r}_I^2} + B_{ij}^- \frac{s_I^- x_3 + s_j^- h}{(r_{Ij}^-)^2} \right], \quad (35)$$
$$T_{\alpha 2}^- = m_{\alpha i}^- \left[B_i \frac{s_I^- x_1}{\overline{r}_I^2} + B_{ij}^- \frac{s_I^- x_1}{(r_{Ij}^-)^2} \right].$$

For material 2 in $x_3 \le 0$, we assume that

$$\psi_i^+ = B_{ij}^+ \left[(s_I^+ x_3 - s_J^- h) \ln r_{Ij}^+ - x_1 \arctan\frac{x_1}{s_I^+ x_3 - s_j^- h} - (s_I^+ x_3 - s_j^- h) \right], \quad (36)$$

where B_{ij}^+ are nine constants to be determined again. With the use of Eq. (36), we rewrite Eqs. (4) and (7) as

$$u_1^+ = -B_{ij}^+ \arctan\frac{x_1}{s_i^+ x_3 - s_j^- h}, \; U_\alpha^+ = k_{\alpha i}^+ B_{ij}^+ s_I^+ \ln r_{Ij}^+, \quad (37)$$

$$\sigma_{11}^+ = -m_{1i}^+ (s_I^+)^2 B_{ij}^+ \frac{s_I^+ x_3 - s_j^- h}{(r_{Ij}^+)^2},$$
$$T_{\alpha 1}^+ = m_{\alpha i}^+ B_{ij}^+ \frac{s_I^+ x_3 - s_j^- h}{(r_{Ij}^+)^2}, \; T_{\alpha 2}^+ = m_{\alpha i}^+ B_{ij}^+ \frac{s_I^+ x_1}{(r_{Ij}^+)^2}. \quad (38)$$

If the two half-planes are ideally bonded, similarly, the conditions listed in Eq. (22) lead to:

$$\begin{aligned} &B_j - \delta_{Ii} B_{ij}^- = \delta_{Ii} B_{ij}^+, \\ &k_{\alpha J}^- s_J^- B_j + k_{\alpha i}^- s_I^- B_{ij}^- = k_{\alpha i}^+ s_I^+ B_{ij}^+, \\ &m_{\alpha J}^- B_j - m_{\alpha i}^- B_{ij}^- = m_{\alpha i}^+ B_{ij}^+, \\ &m_{1J}^- s_J^- B_j + m_{1i}^- s_I^- B_{ij}^- = m_{1i}^+ s_I^+ B_{ij}^+. \end{aligned} \quad (39)$$

Again, when the two half-planes are in smooth contact, the conditions specified by Eq. (23) lead to:

$$\begin{aligned} &k_{\alpha J}^- s_J^- B_j + k_{\alpha i}^- s_I^- B_{ij}^- = k_{\alpha i}^+ s_I^+ B_{ij}^+, \\ &m_{\alpha J}^- B_j - m_{\alpha i}^- B_{ij}^- = m_{\alpha i}^+ B_{ij}^+, \\ &m_{1J}^- s_J^- B_j + m_{1i}^- s_I^- B_{ij}^- = 0, \\ &m_{1i}^+ s_I^+ B_{ij}^+ = 0. \end{aligned} \quad (40)$$

It can also be seen that there are totally 18 independent linear algebraic equations involved in Eq. (39) or Eq. (40), from which the 18 unknown constants B_{ij}^- and B_{ij}^+ can be solved. When the QC materials of the two half-planes are the same, that is, A_{ij}^-, A_{ij}^+, B_{ij}^- and B_{ij}^+ in these equations are equal to zero, the results obtained above reduce directly to those in the previous section for infinite QC planes, provided that h=0.

4 Conclusions

The present paper studies the problem of combination of point phonon and phason forces applied in infinite planes and bi-material planes, which consist of two half-planes of dissimilar 1D orthorhombic QC materials bonded together. Using the general solution of 1D QCs, a series of displacement functions is established, and Green's functions are obtained for infinite planes and two half-planes with point forces applied in the interior of QC planes. The method for deriving the displacements and stresses presented here has some merits. It is straightforward and explicit: the undetermined coefficients are easily determined from the boundary conditions.

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