



## 1. Estimate of Dirichlet Green Tensor

We need the following slight generalization of Van der Corput lemma for the oscillatory integral [3, P.152].

**Lemma 1.1** *Let  $-\infty < a < b < \infty$ , and  $u$  is a  $C^k$  function  $u$  in  $(a, b)$ .*

*1. If  $|u'(t)| \geq 1$  for  $t \in (a, b)$  and  $u'$  is monotone in  $(a, b)$ , then for any  $\phi(t)$  in  $(a, b)$  with integrable derivatives*

$$\left| \int_a^b e^{i\lambda u(t)} \phi(t) dt \right| \leq 3\lambda^{-1} \left[ |\phi(b)| + \int_a^b |\phi'(t)| dt \right].$$

*2. For all  $k \geq 2$ , if  $|u^{(k)}(t)| \geq 1$  for  $t \in (a, b)$ , then for any  $\phi(t)$  in  $(a, b)$  with integrable derivatives*

$$\left| \int_a^b e^{i\lambda u(t)} \phi(t) dt \right| \leq 12k\lambda^{-1/k} \left[ |\phi(b)| + \int_a^b |\phi'(t)| dt \right].$$

**Proof.** The assertion can be proved by extending the Van der Corput lemma in [3]. Here we omit the details.  $\square$

We recall following lemma, see e.g. [6]:

**Lemma 1.2** *Let  $F(\rho, a) = \int_0^a t^{\alpha-1} f(t) e^{-i\rho t} dt$  where  $0 < a \leq +\infty$ ,  $0 < \alpha < 1$ ,  $\rho > 0$  and  $t^{\alpha-1} f \in L^1(0, a)$ , then we have*

$$|F(\rho, a)| \leq C \left( \frac{1}{\rho^\alpha} f(0) + \frac{1}{\rho} (a^{\alpha-1} f(a) + |t^{\alpha-1} f|_{L^1(0, a)}) \right) \quad (1.1)$$

**Proof.** Put

$$g_0(t) = t^{\alpha-1} e^{-i\rho t} \quad (1.2)$$

and define

$$g_1(t) = - \int_t^{t-i\infty} x^{\alpha-1} e^{-i\rho x} dx \quad (1.3)$$

where the path of integration is the vertical line  $x = t - iy, y \geq 0$ . It is easy to show that  $g_1(t)' = g_0(t)$ . Substituting  $x = t - iy$  into  $g_1(t)$ , we have

$$g_1(t) = i \int_0^\infty (t - iy)^{\alpha-1} e^{-i\rho t} e^{-\rho y} dy \quad (1.4)$$

Upon integration by parts, we have

$$\begin{aligned} F(\rho, a) &= \int_0^a f(t) dg_1(t) \\ &= e^{-i\frac{\alpha\pi}{2}} f(0) \Gamma(\alpha) \frac{1}{\rho^\alpha} + f(a) g_1(a) - \int_0^a f'(t) g_1(t) dt \\ &= e^{-i\frac{\alpha\pi}{2}} f(0) \Gamma(\alpha) \frac{1}{\rho^\alpha} - i \int_0^\infty e^{-\rho y} dy \int_0^a f'(t) (t - iy)^{\alpha-1} e^{-i\rho t} dt \end{aligned}$$

Let

$$h(y) = \int_0^a f'(t) (t - iy)^{\alpha-1} e^{-i\rho t} dt$$

and observe that

$$|h(y)| \leq \int_0^a |f'(t)|(t^2 + y^2)^{\frac{\alpha-1}{2}} dt$$

□

**Lemma 1.3** *Let  $F(\rho, a) = \int_0^a t^{-1/2} f(t) e^{-i\rho t} dt$  where  $0 < a \leq +\infty$  and  $\rho > 0$ , then we have*

$$|F(\rho, a) - e^{-i\frac{\pi}{4}} f(0) \Gamma(1/2) \frac{1}{\rho^{1/2}}| \quad (1.5)$$

$$\leq C \left( \int_0^\infty e^{-\rho y} dy \int_0^a |f'(t)|(t^2 + y^2)^{-\frac{1}{4}} dt + \frac{1}{\rho} a^{-1/2} f(a) \right) \quad (1.6)$$

**Proof.** Put

$$g_0(t) = t^{-1/2} e^{-i\rho t} \quad (1.7)$$

and define

$$g_1(t) = - \int_t^{t-i\infty} x^{-1/2} e^{-i\rho x} dx \quad (1.8)$$

where the path of integration is the vertical line  $x = t - iy, y \geq 0$ . It is easy to show that  $g_1(t) = g_0(t)$ . Substituting  $x = t - iy$  into  $g_1(t)$ , we have

$$g_1(t) = i \int_0^\infty (t - iy)^{-1/2} e^{-i\rho t} e^{-\rho y} dy \quad (1.9)$$

Upon integration by parts, we have

$$\begin{aligned} F(\rho, a) &= \int_0^a f(t) dg_1(t) \\ &= e^{-i\frac{\pi}{4}} f(0) \Gamma(1/2) \frac{1}{\rho^{1/2}} + f(a) g_1(a) - \int_0^a f'(t) g_1(t) dt \\ &= e^{-i\frac{\pi}{4}} f(0) \Gamma(1/2) \frac{1}{\rho^{1/2}} + i f(a) \int_0^\infty (a - iy)^{-1/2} e^{-i\rho t} e^{-\rho y} dy \\ &\quad - i \int_0^\infty e^{-\rho y} dy \int_0^a f'(t) (t - iy)^{-1/2} e^{-i\rho t} dt \end{aligned}$$

Let

$$h(y) = \int_0^a f'(t) (t - iy)^{-1/2} e^{-i\rho t} dt$$

and observe that

$$|h(y)| \leq \int_0^a |f'(t)|(t^2 + y^2)^{-\frac{1}{4}} dt$$

It is easy to see that

$$|g_1(a)| \leq a^{-1/2} \int_0^\infty e^{-\rho y} dy \leq C \frac{1}{\rho}$$

□

**Lemma 1.4** Assume that  $0 < \kappa := \sin \phi_\kappa < 1$ ,  $0 < \phi_\kappa < \pi/2$ ,  $0 \leq \phi \leq \pi/2$  and  $-\pi/2 < t_1 < t_2 < \pi/2$  satisfy that  $\kappa^2 = \sin^2(\phi + t_1) = \sin^2(\phi + t_2)$ . Let  $f(\theta)$ :

$$f(t, \phi) := F(\sin(t + \phi), \cos(t + \phi), (\kappa^2 - \sin^2(t + \phi))^{1/2}) \quad (1.10)$$

be a function in  $C^\infty(([-\pi/2, \pi/2] \setminus \{t_1, t_2\}) \times [0, \pi/2])$ . Moreover, there exists  $\epsilon > 0$  such that  $f(\theta)$  can be represented as

$$f(t, \phi) = g_1(t, \phi) + g_2(t, \phi)(\kappa^2 - \sin^2(t + \phi))^{1/2})^{N/2} \quad (1.11)$$

where  $g_1, g_2 \in C^\infty((\bigcup_{i=1,2} (t_i - \epsilon, t_i + \epsilon)) \times [0, \pi/2])$  and  $N = \pm 1$ . Then for any  $\rho \geq 1$ , we have

$$\begin{aligned} |I(\rho, \phi) &:= \int_{-\pi/2}^{\pi/2} f(\theta) e^{i\rho \cos \theta} d\theta - \frac{N+1}{2} \left(\frac{2\pi}{\rho}\right)^{1/2} f(0) e^{i\rho - i\pi/4}| \\ &\leq C \frac{1}{\rho^{(2+N)/4}} \end{aligned} \quad (1.12)$$

**Proof.** The proof will be split into two parts about whether  $\phi$  equal to  $\phi_\kappa$ .

If  $\phi \neq \phi_\kappa$ , there exists  $0 < \delta < \pi/4$  such that

$$|(\kappa^2 - \sin^2(t + \phi))^{1/2}| > \frac{1}{2} |(\kappa^2 - \sin^2 \phi)^{1/2}| \quad (1.13)$$

for any  $t \in (-\delta, \delta)$ . Let  $\chi_\delta \in C_0^\infty(-\pi/2, \pi/2)$  be the cut-off function with that  $0 \leq \chi_\delta \leq 1$ ,  $\chi_\delta = 1$  in  $(-\delta/2, \delta/2)$  and  $\chi_\delta = 0$  in  $(-\pi/2, \pi/2) \setminus (-\delta, \delta)$ . Then we can divide  $I$  into two parts such that

$$\begin{aligned} I &= \int_{-\delta}^{\delta} f(t) \chi_\delta(t) e^{i\rho \cos t} dt + \int_{-\pi/2}^{\pi/2} f(t) (1 - \chi_\delta(t)) e^{i\rho \cos t} dt \\ &=: I_1 + I_2 \end{aligned}$$

Substituting  $t(s) = 2 \arcsin s/2$  for  $t$  in  $I_1$ , we can obtain

$$I_1 = \int_{\mathbb{R}} f(t(s)) \chi_\delta(t(s)) \frac{1}{\sqrt{1 - s^2/4}} e^{i\rho} e^{-i\rho s^2/2} ds \quad (1.14)$$

$$= \int_{\mathbb{R}} h_\delta(s) e^{i\rho} e^{-i\rho s^2/2} ds \quad (1.15)$$

It is easy to see that  $h_\delta(s) \in C_0^4(\mathbb{R})$ . By the lemma of the stationary phase for quadratic term in [2], we have

$$I_1 = e^{i\rho} \int_{\mathbb{R}} h_\delta(s) e^{-i\frac{\rho}{2}s^2} ds = e^{i\rho} \int_{\mathbb{R}} \widehat{h}_\delta(y) \alpha(-y) dy \quad (1.16)$$

where

$$\alpha(y) = \left(\frac{1}{2\pi\rho}\right)^{1/2} e^{-i\pi/4} e^{\frac{i}{2\rho}y^2} \quad (1.17)$$

$$= \left(\frac{1}{2\pi\rho}\right)^{1/2} e^{-i\pi/4} (1 + O(\frac{y^2}{\rho})) \quad (1.18)$$

Consequently

$$I_1 = \left(\frac{1}{2\pi\rho}\right)^{1/2} e^{i\rho - i\pi/4} \int_{\mathbb{R}} \widehat{h}_\delta(y) (1 + \frac{1}{\rho} O(y^2)) dy \quad (1.19)$$

Moreover,  $\int_{\mathbb{R}} \widehat{h}_\delta(y) dy = 2\pi h_\delta(0)$  and  $|\int_{\mathbb{R}} \widehat{h}_\delta(y) y^2 dy| < C$  since  $\widehat{h}_\delta(y) = O(1/y^4)$ . Now, it turns to estimate  $I_2$ .

When  $N = 1$ , using integration by parts, we have

$$|I_2| = \left| \int_{(-\frac{\pi}{2}, \frac{\pi}{2}) \setminus (-\frac{\delta}{2}, \frac{\delta}{2})} f(t)(1 - \chi_\delta(t)) / \sin t \, de^{i\rho \cos t} \right| \quad (1.20)$$

$$(1.21)$$

$$\leq C \frac{1}{\rho} + \left| \int_{(-\frac{\pi}{2}, \frac{\pi}{2}) \setminus (-\frac{\delta}{2}, \frac{\delta}{2})} (f(t)(1 - \chi_\delta(t)) / \sin t)' e^{i\rho \cos t} dt \right| \quad (1.22)$$

$$\leq C \frac{1}{\rho} \quad (1.23)$$

From above analysis, we obtain

$$\left| I(\rho, \phi) - \left( \frac{2\pi}{\rho} \right)^{1/2} f(0) e^{i\rho - i\pi/4} \right| \leq C(\phi) \frac{1}{\rho} \quad (1.24)$$

When  $N = -1$ , we can not use integration by parts again since  $f'(\theta)$  is not integrable. However, for any  $0 < \lambda_1 < 1$  and  $1 < \lambda_2 < 1/\kappa$ , there exists  $0 < \sigma < \epsilon$ , such that  $\chi := ((t_1 - \sigma, t_1 + \sigma) \cup (t_2 - \sigma, t_2 + \sigma)) \cap (-\delta, \delta) = \emptyset$ , dependent on  $\lambda_1, \lambda_2$  and

$$\lambda_1 \kappa < |\sin(t + \phi)| < \lambda_2 \kappa. \quad (1.25)$$

for any  $t \in \chi$ .

We only analysis the integral on  $\chi_1 = (t_1 - \sigma, t_1 + \sigma) \cap [-\pi/2, \pi/2]$  here, which denoted by  $I_{\chi_1}$ , the proof of  $I_{\chi_2}$  is similar. It is easy to see that  $\sin(t + \phi)$  is monotonic in  $\chi_1$ . Without loss of generality, we assume that  $\sin(t_1 - \sigma + \phi) < \kappa < \sin(t_1 + \sigma + \phi)$ . Let  $\sin(t + \phi) = \kappa \sin \theta$  and the implicit mapping from  $\theta$  to  $t$  is denoted by  $t(\theta)$  while the inverse mapping by  $\theta(t)$ , taking the interval  $\chi_1$  onto  $L_\theta : \theta_1 \rightarrow \pi/2 \rightarrow \pi/2 - i\theta_2$  where  $\sin(t_1 - \sigma + \phi) = \kappa \sin \theta_1, \sin(t_1 + \sigma + \phi) = \kappa \sin(\pi/2 - i\theta_2)$ . By substituting  $t(\theta)$  into  $I_{\chi_1}$ , we have

$$I_{\chi_1} = \int_{t_1 - \sigma}^{t_1 + \sigma} \frac{f(t)(\kappa^2 - \sin^2(t + \phi))^{1/2}}{(\kappa^2 - \sin^2(t + \phi))^{1/2}} e^{i\rho \cos t} \quad (1.26)$$

$$= \int_{L_\theta} \frac{\kappa f(t(\theta)) \cos \theta}{(1 - \kappa^2 \sin^2 \theta)^{1/2}} e^{i\rho(\cos(t(\theta)))} d\theta \quad (1.27)$$

$$= \int_{L_\theta} \frac{\kappa g_1(t(\theta)) \cos \theta + g_2(t(\theta))}{(1 - \kappa^2 \sin^2 \theta)^{1/2}} e^{i\rho(\cos(t(\theta)))} d\theta \quad (1.28)$$

$$:= \int_{L_\theta} \frac{h(\theta)}{(1 - \kappa^2 \sin^2 \theta)^{1/2}} e^{i\rho(\cos(t(\theta)))} d\theta \quad (1.29)$$

Observe that  $h(\theta)$  and  $\partial h / \partial \theta$  are integrable on the path  $L_\theta$  by (1.11). A simple computation show that

$$\frac{dt(\theta)}{d\theta} = \frac{\kappa \cos \theta}{\cos(t + \phi)} \quad \frac{d^2 t(\theta)}{d\theta^2} = \frac{\kappa^2 \cos^2 \theta \sin(t + \phi) - \kappa \sin \theta \cos^2(t + \phi)}{\cos^3(t + \phi)}$$

Then we can obtain

$$\frac{d \cos t}{d\theta} = \frac{-\kappa \sin t \cos \theta}{\cos(t + \phi)}$$

$$\begin{aligned}
\frac{d^2 \cos t}{d\theta^2} &= \frac{d^2 \cos t}{dt^2} \left( \frac{dt}{d\theta} \right)^2 + \frac{d \cos t}{dt} \frac{d^2 t}{d\theta^2} \\
&= \frac{-\kappa^2 \cos^2 \theta \cos t}{\cos^2(t + \phi)} + \frac{\kappa \sin \theta \cos^2(t + \phi) \sin t - \kappa^2 \cos^2 \theta \sin(t + \phi) \sin t}{\cos^3(t + \phi)} \\
&= \frac{-\kappa^2 \cos^2 \theta \cos \phi + \kappa \sin \theta \cos^2(t + \phi) \sin t}{\cos^3(t + \phi)} \\
&= \frac{(\sin^2(t + \phi) - \kappa^2) \cos \phi + \cos^2(t + \phi) \sin(t + \phi) \sin t}{\cos^3(t + \phi)}
\end{aligned}$$

Since  $|\sin t| > |\sin \delta|$  and  $1 - \lambda_2^2 \kappa^2 < \cos^2(t + \phi) < 1 - \lambda_1^2 \kappa^2$  for  $t \in \chi_1$ , it follows that  $\theta = \pi/2$  is the only stationary point of  $\cos(t(\theta))$  and

$$\left| \frac{d^2 \cos t}{d\theta^2}(\pi/2) \right| = \frac{(1 - \kappa^2)\kappa}{(1 - \kappa^2)^{3/2}} |\sin t| > \frac{(1 - \kappa^2)\kappa}{(1 - \kappa^2)^{3/2}} \sin \delta \quad (1.30)$$

Therefore, we can choose appropriate  $\lambda_1, \lambda_2$  such that

$$\left| \frac{d^2 \cos t}{d\theta^2} \right| > \frac{(1 - \kappa^2)\kappa}{(1 - \kappa^2)^{3/2}} \sin \delta \quad (1.31)$$

for any  $\theta \in \theta(\chi_1)$ . According to lemma (6.1), we obtain  $|I_{\chi_1}| \leq C \frac{1}{\rho^{1/2}}$ , and also  $|I_{\chi_2}| \leq C \frac{1}{\rho^{1/2}}$ . Using integration by parts, we get

$$\left| \int_{[-\pi/2, \pi/2] \setminus ((-\delta, \delta) \cup \chi)} f(t)(1 - \chi_\delta(t)) e^{i\rho \cos t} dt \right| \leq C \frac{1}{\rho}$$

Consequently, for  $N = -1$  and  $\phi \neq \phi_\kappa$ , we get  $|I(\rho, \phi)| \leq \frac{1}{\rho^{1/2}}$ .

We now turn to the case of  $\phi = \phi_\kappa$ . By (1.11), we can define  $\chi_\epsilon$  similarly and also decompose  $I$  into  $I_1$  and  $I_2$ . Using the same argument above, we can easily carry out that: for  $N = 1$ , we have  $|I_2| \leq C \frac{1}{\rho}$ ; for  $N = -1$ , we have  $|I_2| \leq C \frac{1}{\rho^{1/2}}$ . Finally, it remains to analysis  $I_1$ . By (1.11), we have

$$\begin{aligned}
I_1 &= \int_{-\epsilon}^{\epsilon} g_1 \chi_\epsilon + g_2 \chi_\epsilon (\sin^2 \phi_\kappa - \sin^2(t + \phi_\kappa))^{N/2} e^{i\rho \cos t} dt \\
&= \int_{-\epsilon}^{\epsilon} g_1 \chi_\epsilon + g_2 \chi_\epsilon (-2(\sin \phi_\kappa + \sin(t + \phi_\kappa)) \cos \frac{2\phi_\kappa + t}{2} \sin t/2)^{N/2} e^{i\rho \cos t} dt \\
&= \int_{\mathbb{R}} g_1 \chi_\epsilon + g_2 \chi_\epsilon ((\sin \phi_\kappa + \sin(t + \phi_\kappa)) \cos \frac{2\phi_\kappa + t}{2})^{N/2} (-2 \sin t/2)^{N/2} e^{i\rho \cos t} dt
\end{aligned}$$

Also, substituting  $t(s) = 2 \arcsin s/2$  for  $t$  in  $I_1$ , it follows that

$$I_1 = \int_{\mathbb{R}} h_1(s) e^{-i\rho \frac{s^2}{2}} + h_2(s) (-s)^{N/2} e^{-i\rho \frac{s^2}{2}} \quad (1.32)$$

$$= I_{11} + I_{12} \quad (1.33)$$

where

$$\begin{aligned}
h_1(s) &= g_1(t(s)) \chi_\epsilon(t(s)) \sqrt{1 - s^2/4} e^{i\rho} \\
h_2(s) &= g_2 \chi_\epsilon((\sin \phi_\kappa + \sin(t + \phi_\kappa)) \cos \frac{2\phi_\kappa + t}{2})_{t=t(s)}^{N/2} \sqrt{1 - s^2/4} e^{i\rho}
\end{aligned}$$

and  $h_1(s), h_2(s) \in C_c^\infty(\mathbb{R})$ . Using stationary phase lemma similarly, if  $N = 1$ ,

$$I_{11} = \left(\frac{2\pi}{\rho}\right)^{1/2} g_1(0) e^{\mathbf{i}\rho - \mathbf{i}\pi/4} + O\left(\frac{1}{\rho}\right) \quad (1.34)$$

$$= \left(\frac{2\pi}{\rho}\right)^{1/2} f(0) e^{\mathbf{i}\rho - \mathbf{i}\pi/4} + O\left(\frac{1}{\rho}\right) \quad (1.35)$$

if  $N = -1$ , we get  $|I_{11}| \leq C \frac{1}{\rho^{1/2}}$ . For  $I_{12}$ , we have

$$I_{12} = \int_0^\infty (\mathbf{i}h_2(s) + h_2(-s)) s^{N/2} e^{-\mathbf{i}\rho s^2/2} ds \quad (1.36)$$

$$= \frac{1}{2} \int_0^\infty (\mathbf{i}h_2(\sqrt{s}) + h_2(-\sqrt{s})) s^{N/4-1/2} e^{-\mathbf{i}\rho s/2} ds \quad (1.37)$$

By lemma (1.2), we get  $|I_{12}| \leq C \frac{1}{\rho^{(N+2)/4}}$ .  $\square$

## 2. Some draft about Green Tensor Analysis

Let substitute  $\xi = k \sin \theta$  into integral and shift the variable, we have

$$I(y) = \int_{\mathbb{R}} f(\xi) e^{\mathbf{i}\xi y_1 + \mu(\xi) y_2} d\xi = \int_{\mathbb{R}} f(\xi) e^{\mathbf{i}\xi(y_1 - z_1) + \mu(\xi)(y_2 - z_2)} e^{\mathbf{i}\xi z_1 + \mu(\xi) z_2} d\xi \quad (2.1)$$

$$= k \int_L f(k \sin \theta) \cos \theta e^{\mathbf{i}k|y-z| \cos(\theta-\eta)} e^{\mathbf{i}|z| \cos(\theta-\phi)} d\theta \quad (2.2)$$

$$= k \int_{L_\phi} f(k \sin(\theta + \phi)) \cos(\theta + \phi) e^{\mathbf{i}k|y-z| \cos(\theta+\phi-\eta)} e^{\mathbf{i}|z| \cos \theta} d\theta \quad (2.3)$$

$$= k \int_L f(k \sin(\theta + \phi)) \cos(\theta + \phi) e^{\mathbf{i}k|y-z| \cos(\theta+\phi-\eta)} e^{\mathbf{i}|z| \cos \theta} d\theta \quad (2.4)$$

where  $y_1, y_2 > 0$ ,  $\sin \phi = \frac{z_1}{|z|}$ ,  $\cos \phi = \frac{z_2}{|z|}$ ,  $0 < \phi < \pi/2$  and  $\sin \eta = \frac{y_1 - z_1}{|y-z|}$ ,  $\cos \eta = \frac{y_2 - z_2}{|y-z|}$ ,  $0 < \eta < \pi$ . It is easy to see that  $\phi + \eta < \pi$ . Roughly, using stationary phase lemma, we obtain:

$$I(y) = f(k \sin \phi) k \cos \phi e^{\mathbf{i}k|y-z| \cos(\phi-\eta)} \left(\frac{2\pi}{|z|}\right)^{1/2} e^{\mathbf{i}|z| - \mathbf{i}\frac{\pi}{4}} (1 + O(\frac{1}{|z|})) \quad (2.5)$$

$$\cos(a + \mathbf{i}b) = \frac{e^b + e^{-b}}{2} \cos a + \mathbf{i} \frac{e^{-b} - e^b}{2} \sin a \quad (2.6)$$

$$\sin(a + \mathbf{i}b) = \frac{e^b + e^{-b}}{2} \sin a + \mathbf{i} \frac{e^b - e^{-b}}{2} \cos a \quad (2.7)$$

When  $\theta \in (-a - \pi/2, -a - \pi/2 + \mathbf{i}\infty)$ , let  $\theta = -a - \pi/2 + \mathbf{i}t$ , where  $t > 0$ ,  $0 \leq a \leq \phi$ , then

$$\begin{aligned} & -\text{Im}(|z| \cos \theta + |y-z| \cos(\theta + \phi - \eta)) \\ &= |z| \sin(a + \pi/2) + |y-z| \sin(a + \pi/2 - \phi + \eta) \end{aligned} \quad (2.8)$$

$$= |z| \cos a + |y-z| \cos(a - \phi + \eta) \quad (2.9)$$

$$= |z| \cos a + \cos a |y-z| (\cos \phi \cos \eta + \sin \phi \sin \eta) \quad (2.10)$$

$$+ \sin a |y-z| (\sin \phi \cos \eta - \cos \phi \sin \eta) \quad (2.11)$$

$$= |z| \cos a + \cos a((y_2 - z_2) \cos \phi + (y_1 - z_1) \sin \phi) \quad (2.12)$$

$$+ \sin a((y_2 - z_2) \sin \phi - (y_1 - z_1) \cos \phi) \quad (2.13)$$

$$= y_1 \sin(\phi - a) + y_2 \cos(\phi - a) > 0 \quad (2.14)$$

Now, Using Cauchy Integral Theorem, we have

$$I(y) = k \int_L f(k \sin(\theta + \phi)) \cos(\theta + \phi) e^{\mathbf{i}k|y-z| \cos(\theta+\phi-\eta)} e^{\mathbf{i}|z| \cos \theta} d\theta \quad (2.15)$$

Let  $L_1 = (-\pi/2, -\pi/2 + \mathbf{i}\infty)$  and  $\theta = -\pi/2 + \mathbf{i}t, t > 0$ , then

$$I_1(y) = k \int_{L_1} f(k \sin(\theta + \phi)) \cos(\theta + \phi) e^{\mathbf{i}k|y-z| \cos(\theta+\phi-\eta)} e^{\mathbf{i}|z| \cos \theta} d\theta \quad (2.16)$$

$$= \quad (2.17)$$

$$I(y) = f(k \sin \phi) k \cos \phi e^{\mathbf{i}k|y-z| \cos(\phi-\eta)} \left(\frac{2\pi}{|z|}\right)^{1/2} e^{\mathbf{i}|z| - \mathbf{i}\frac{\pi}{4}} \quad (2.18)$$

$$+ \frac{kz_2}{|z|} O\left(\left(\frac{1}{k|z|}\right)^{3/4} + \frac{1}{k|y|}\right) + \frac{kz_1}{|z|} O\left(\left(\frac{1}{k|z|}\right)^{5/4} + \left(\frac{1}{k|y|}\right)^2\right) \quad (2.19)$$

It is easy to see

$$\int_{-d}^d \frac{k}{(k|x-z|)^\alpha} \frac{1}{(k|x-y|)^\beta} dx_1 \leq C \left( \frac{1}{(kz_2)^{\alpha+\beta-1}} + \frac{1}{(ky_2)^{\alpha+\beta-1}} \right) \quad (2.20)$$

where  $z, y \in \mathbb{R}_+^2$ ,  $x \in \Gamma_0$  and  $\alpha + \beta > 0$ .

$$e^{\mathbf{i}\mu y_2 + \mathbf{i}\xi(x_1 - y_1)} = e^{\mathbf{i}\mu y_2 - \mathbf{i}y_2 / \tan \phi} = e^{\mathbf{i}y_2(\mu - \xi / \tan \phi)} \quad (2.21)$$

Another method

$$\int_{-\pi/2}^{\pi/2} f(k \sin(\theta + \psi)) k \cos(\theta + \psi) e^{\mathbf{i}k|x-y| \cos \theta} \quad (2.22)$$

$$= \int_{-\pi/2}^{\pi/2} f(k \sin(\theta + \psi)) k \cos(\theta + \psi) e^{\mathbf{i}k|x-y| \cos(\theta+\psi-\psi)} \quad (2.23)$$

$$= \int_{-\pi/2}^{\pi/2} f(k \sin(\theta + \psi)) k \cos(\theta + \psi) e^{\mathbf{i}ky_2 \cos(\theta+\psi) + \mathbf{i}k|x_1 - y_1| \sin(\theta+\psi)} \quad (2.24)$$

$$= \int_{-\pi/2}^{\pi/2} f(k \sin(\theta + \psi)) k \cos(\theta + \psi) \quad (2.25)$$

$$e^{\mathbf{i}k(y_2 - z_2) \cos(\theta+\psi) + \mathbf{i}k(|x_1 - y_1| - |x_1 - z_1|) \sin(\theta+\psi) + \mathbf{i}k|z| \cos(\theta+\psi-\phi)} \quad (2.26)$$

### 3. Finite Aperture Point Spread Function

If  $x \in \Gamma_0$  and  $z, y \in \mathbb{R}_+^2$ , by lemma (??) we have

$$\begin{aligned} G(x, y) &= \frac{\mathbf{i}k_s}{\mu\sqrt{2\pi}} \frac{1}{\delta(\xi)} \begin{pmatrix} \mu_s \beta & \xi \beta \\ 2\xi \mu_s \mu_p & 2\xi^2 \mu_p \end{pmatrix}_{\xi=k_s \frac{x_1 - y_1}{|x - y|}} \frac{y_2}{|x - y|} \frac{1}{(k_s |x - y|)^{1/2}} e^{\mathbf{i}k_s |x - y| - \mathbf{i}\frac{\pi}{4}} \\ &+ \frac{\mathbf{i}k_p}{\mu\sqrt{2\pi}} \frac{1}{\delta(\xi)} \begin{pmatrix} 2\xi^2 \mu_s & -2\xi \mu_s \mu_p \\ -\xi \beta & \mu_p \beta \end{pmatrix}_{\xi=k_p \frac{x_1 - y_1}{|x - y|}} \frac{y_2}{|x - y|} \frac{1}{(k_p |x - y|)^{1/2}} e^{\mathbf{i}k_p |x - y| - \mathbf{i}\frac{\pi}{4}} \end{aligned} \quad (3.1)$$



$$\begin{aligned}
& +O\left(\frac{y_2}{|x-y|} \frac{1}{(k_s|x-y|)^{3/4}} + \frac{|x_1-y_1|}{|x-y|} \frac{1}{(k_s|x-y|)^{5/4}}\right) \\
& := \mathcal{G}_s(x, y) + \mathcal{G}_p(x, y) + O\left(\frac{y_2}{|x-y|} \frac{1}{(k_s|x-y|)^{3/4}} + \frac{|x_1-y_1|}{|x-y|} \frac{1}{(k_s|x-y|)^{5/4}}\right) \\
T_D(x, z) &= \frac{k_s}{\sqrt{2\pi}} \frac{1}{\gamma(\xi)} \begin{pmatrix} \mu_s \mu_p & \xi \mu_p \\ \xi \mu_s & \xi^2 \end{pmatrix}_{\xi=k_s \frac{x_1-z_1}{|x-z|}} \frac{z_2}{|x-z|} \frac{1}{(k_s|x-z|)^{1/2}} e^{i k_s |x-z| - i \frac{\pi}{4}} \\
& + \frac{k_p}{\sqrt{2\pi}} \frac{1}{\gamma(\xi)} \begin{pmatrix} \xi^2 & -\xi \mu_p \\ -\xi \mu_s & \mu_p \mu_s \end{pmatrix}_{\xi=k_p \frac{x_1-z_1}{|x-z|}} \frac{z_2}{|x-z|} \frac{1}{(k_p|x-z|)^{1/2}} e^{i k_p |x-z| - i \frac{\pi}{4}} \quad (3.2) \\
& + O\left(\frac{k_s z_2}{|x-z|} \frac{1}{(k_s|x-z|)^{3/4}} + \frac{k_s |x_1-z_1|}{|x-z|} \frac{1}{(k_s|x-z|)^{5/4}}\right) \\
& := \mathcal{T}_s(x, z) + \mathcal{T}_p(x, z) + O\left(\frac{k_s z_2}{|x-z|} \frac{1}{(k_s|x-z|)^{3/4}} + \frac{k_s |x_1-z_1|}{|x-z|} \frac{1}{(k_s|x-z|)^{5/4}}\right)
\end{aligned}$$

Now we consider the finite aperture point spread function  $J_d(z, y)$ :

$$\int_{-d}^d (T_D(x_1, 0; z_1, z_2))^T \overline{G(x_1, 0; y_1, y_2)} dx_1 \quad (3.3)$$

Recall following standard asymptotic expansion:

$$|x-y| = |x-z| + \widehat{x-z} \cdot (z-y) + O\left(\frac{|y-z|^2}{|x-z|}\right) \quad (3.4)$$

$$|y|^{-\alpha} = |z|^{-\alpha} \left(1 + \frac{|y|-|z|}{|z|}\right)^{-\alpha} = |z|^{-\alpha} \left(1 + O\left(\frac{|y-z|}{|z|}\right)\right) \quad (3.5)$$

$$e^{it} = 1 + O(t) \quad (3.6)$$

$$|a^{1/2} - b^{1/2}| \leq C \sqrt{|a-b|} \quad (3.7)$$

where  $x, y, z \in \mathbb{R}^2$ ,  $t, a, b \in \mathbb{R}$  and  $\alpha > 0$ .

**Lemma 3.1** For any  $z, y \in \mathbb{R}_+^2$ ,  $J_d(z, y) = F(z, y) + O\left((1 + \frac{|y-z|}{z_2}) \left(\frac{1}{k_s z_2}\right)^{1/4} + \frac{(k_s |y-z|)^2}{k_s z_2} + \left(\frac{|y-z|}{z_2}\right)^{1/2}\right)$ , where

$$F(z, y) = -\frac{\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} f_s(\theta) \begin{pmatrix} \sin^2 \theta & \sin \theta \cos \theta \\ \sin \theta \cos \theta & \cos^2 \theta \end{pmatrix} e^{i k_s (z_1 - y_1) \cos \theta + i k_s (z_2 - y_2) \sin \theta} d\theta \quad (3.8)$$

$$-\frac{\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} f_p(\theta) \begin{pmatrix} \cos^2 \theta & -\sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin^2 \theta \end{pmatrix} e^{i k_p (z_1 - y_1) \cos \theta + i k_p (z_2 - y_2) \sin \theta} d\theta \quad (3.9)$$

and

$$\begin{aligned}
f_s(\theta) &= \frac{\sin \theta ((\kappa^2 - \cos^2 \theta)^{1/2} (1 - 2 \cos^2 \theta) + 2(\kappa^2 - \cos^2 \theta)^{1/2} \cos^2 \theta)}{(\cos^2 \theta + \sin \theta (\kappa^2 - \cos^2 \theta)^{1/2}) ((1 - 2 \cos^2 \theta)^2 + 4 \cos^2 \theta \sin \theta (\kappa^2 - \cos^2 \theta)^{1/2})} \\
f_p(\theta) &= \frac{\sin \theta (1/\kappa^2 - \cos^2 \theta)^{1/2}}{(\cos^2 \theta + \sin \theta (1/\kappa^2 - \cos^2 \theta)^{1/2}) ((1/\kappa^2 - 2 \cos^2 \theta)^2 + 4 \cos^2 \theta \sin \theta (1/\kappa^2 - \cos^2 \theta)^{1/2})}
\end{aligned}$$

where  $0 < \theta_1^d < \pi/2 < \theta_2^d < \pi$  and  $z_2 = (d + z_1) \tan \theta_1^d = (z_1 - d) \tan \theta_2^d$ .

**Proof.**

$$\begin{aligned}
& \frac{y_2}{|x-y|} \frac{1}{(k_s|x-y|)^{3/4}} + \frac{|x_1-y_1|}{|x-y|} \frac{1}{(k_s|x-y|)^{5/4}} \\
&= \left( \frac{z_2}{|x-z|} \frac{1}{(k_s|x-z|)^{3/4}} + \frac{|x_1-z_1|}{|x-z|} \frac{1}{(k_s|x-z|)^{5/4}} \right) (1 + O(\frac{|y-z|}{|x-z|})) \\
& \quad |\mu_i(k_j \frac{x_1-y_1}{|x-y|}) - \mu_i(k_j \frac{x_1-z_1}{|x-z|})| \\
& \leq Ck_j \sqrt{\left| \frac{x_1-y_1}{|x-y|} - \frac{x_1-z_1}{|x-z|} \right|} \leq Ck_j \left( \frac{|y-z|}{|x-z|} \right)^{1/2}
\end{aligned}$$

where  $i, j = s, p$ . By above, we can obtain

$$\mathcal{G}_s(x, y) = \mathcal{G}_s(x, z) e^{\widehat{ik_s x - z} \cdot (z-y)} + O\left(\frac{(k_s|y-z|)^2}{(k_s|x-z|)^{3/2}}\right) + O\left(\frac{(k_s|y-z|)^{1/2}}{k_s|x-z|}\right) \quad (3.10)$$

$$\mathcal{G}_p(x, y) = \mathcal{G}_p(x, z) e^{\widehat{ik_p x - z} \cdot (z-y)} + O\left(\frac{(k_p|y-z|)^2}{(k_p|x-z|)^{3/2}}\right) + O\left(\frac{(k_p|y-z|)^{1/2}}{k_p|x-z|}\right) \quad (3.11)$$

For  $l > 1$ , a simple computation show that

$$\int_{-d}^d \frac{k_s}{(k_s|x-z|)^l} dx_1 = \frac{1}{(k_s z_2)^{l-1}} \int_{\frac{-d-z_1}{z_2}}^{\frac{d-z_1}{z_2}} \frac{1}{(1+t^2)^{l/2}} dt \leq C \frac{1}{(k_s z_2)^{l-1}} \quad (3.12)$$

Let

$$\mathcal{G}_\alpha(x, y) = \frac{\mathbf{i}}{\sqrt{2\pi\mu}} g_\alpha\left(\frac{x_1-y_1}{|x-y|}, \kappa\right) \frac{1}{(k_\alpha|x-y|)^{1/2}} e^{\mathbf{i}k_\alpha|x-y| - \mathbf{i}\frac{\pi}{4}} \quad (3.13)$$

$$\mathcal{T}_\alpha(x, y) = \frac{k_\alpha}{\sqrt{2\pi}} t_\alpha\left(\frac{x_1-z_1}{|x-z|}, \kappa\right) \frac{1}{(k_s|x-z|)^{1/2}} e^{\mathbf{i}k_\alpha|x-z| - \mathbf{i}\frac{\pi}{4}} \quad (3.14)$$

where  $\alpha = s, p$ . Now, by substituting (3.10-3.11) into  $J_d(z, y)$  and using inequality (3.12), we have

$$\begin{aligned}
J_d(z, y) &= \frac{-\mathbf{i}}{2\pi\mu} \int_{-d}^d t_s\left(\frac{x_1-z_1}{|x-z|}, \kappa\right) \overline{g_s\left(\frac{x_1-z_1}{|x-z|}, \kappa\right)} \frac{e^{\widehat{ik_s x - z} \cdot (y-z)}}{|x-z|} \\
& \quad + t_p\left(\frac{x_1-z_1}{|x-z|}, \kappa\right) \overline{g_p\left(\frac{x_1-z_1}{|x-z|}, \kappa\right)} \frac{e^{\widehat{ik_p x - z} \cdot (y-z)}}{|x-z|} dx_1 \quad (3.15)
\end{aligned}$$

$$- \frac{\mathbf{i}}{2\pi\mu} \int_{-d}^d t_p\left(\frac{x_1-z_1}{|x-z|}, \kappa\right) \overline{g_s\left(\frac{x_1-z_1}{|x-z|}, \kappa\right)} \frac{e^{\widehat{ik_s x - z} \cdot (y-z)}}{|x-z|} \quad (3.16)$$

$$+ t_s\left(\frac{x_1-z_1}{|x-z|}, \kappa\right) \overline{g_p\left(\frac{x_1-z_1}{|x-z|}, \kappa\right)} \frac{e^{\widehat{ik_p x - z} \cdot (y-z)}}{|x-z|} dx_1 \quad (3.17)$$

$$+ O\left((1 + \frac{|y-z|}{z_2}) \left(\frac{1}{k_s z_2}\right)^{1/4} + \frac{(k_s|y-z|)^2}{k_s z_2} + \left(\frac{|y-z|}{z_2}\right)^{1/2}\right) \quad (3.18)$$

$$:= F(z, y) + R(z, y) \quad (3.19)$$

$$+ O\left((1 + \frac{|y-z|}{z_2}) \left(\frac{1}{k_s z_2}\right)^{1/4} + \frac{(k_s|y-z|)^2}{k_s z_2} + \left(\frac{|y-z|}{z_2}\right)^{1/2}\right) \quad (3.20)$$

We denote  $\widehat{x-z} = x-z/|x-z| = (\cos(\phi+\pi), \sin(\phi+\pi))$ , then taking the substitution  $x_1 = z_1 - z_2 \cot \phi$ , we obtain

$$F(z, y) = \frac{-\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} A_s(\phi, \kappa) e^{\mathbf{i}k_s(z_1-y_1) \cos \phi + \mathbf{i}k_s(z_2-y_2) \sin \phi} \quad (3.21)$$

$$+ \frac{-\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} A_p(\phi, \kappa) e^{\mathbf{i}k_p(z_1-y_1) \cos \phi + \mathbf{i}k_p(z_2-y_2) \sin \phi} \quad (3.22)$$

$$R(z, y) = \frac{-\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} B_s(\phi, \kappa) e^{\mathbf{i}k_s(z_1-y_1) \cos \phi + \mathbf{i}k_s(z_2-y_2) \sin \phi + (k_p-k_s)|x-z|} \quad (3.23)$$

$$+ \frac{-\mathbf{i}}{2\pi\mu} \int_{\theta_1^d}^{\theta_2^d} B_p(\phi, \kappa) e^{\mathbf{i}k_p(z_1-y_1) \cos \phi + \mathbf{i}k_p(z_2-y_2) \sin \phi + (k_s-k_p)|x-z|} \quad (3.24)$$

It is easy to see that  $|R(z, y)| \leq C \frac{|z-y|}{z_2}$ .  $\square$

Let

$$g(x_1) = \frac{1}{((x_1 - z_1)^2 + z_2^2)^{3/4} ((x_1 - y_1)^2 + y_2^2)^{1/4}}$$

$$\phi(x_1) = ((x_1 - z_1)^2 + z_2^2)^{1/2} - ((x_1 - y_1)^2 + y_2^2)^{1/2}$$

Then, we have

$$g'(x_1) = -g(x_1) \left[ \frac{3(x_1 - z_1)}{2((x_1 - z_1)^2 + z_2^2)} + \frac{(x_1 - y_1)}{2((x_1 - y_1)^2 + y_2^2)} \right]$$

$$\phi'(x_1) = \frac{x_1 - z_1}{((x_1 - z_1)^2 + z_2^2)^{1/2}} - \frac{x_1 - y_1}{((x_1 - y_1)^2 + y_2^2)^{1/2}}$$

$$= \frac{\frac{(x_1 - z_1)^2}{(x_1 - z_1)^2 + z_2^2} - \frac{(x_1 - y_1)^2}{(x_1 - y_1)^2 + y_2^2}}{\frac{x_1 - z_1}{((x_1 - z_1)^2 + z_2^2)^{1/2}} + \frac{x_1 - y_1}{((x_1 - y_1)^2 + y_2^2)^{1/2}}}$$

$$= \frac{(x_1 - z_1)^2 y_2^2 - (x_1 - y_1)^2 z_2^2}{\left( \frac{x_1 - z_1}{((x_1 - z_1)^2 + z_2^2)^{1/2}} + \frac{x_1 - y_1}{((x_1 - y_1)^2 + y_2^2)^{1/2}} \right) ((x_1 - z_1)^2 + z_2^2) ((x_1 - y_1)^2 + y_2^2)}$$

$$\phi''(x_1) = \frac{z_2^2}{((x_1 - z_1)^2 + z_2^2)^{3/2}} - \frac{y_2^2}{((x_1 - y_1)^2 + y_2^2)^{3/2}}$$

Using integration by parts, we can obtain

$$\int_{-d}^d g(x_1) e^{\mathbf{i}\phi(x_1)} dx_1$$

$$= \left( \frac{g(d)}{\phi'(d)} e^{\mathbf{i}\phi(d)} - \frac{g(-d)}{\phi'(-d)} e^{\mathbf{i}\phi(-d)} \right) - \int_{-d}^d \frac{g'(x_1)}{\phi'(x_1)} - \frac{g(x_1)\phi''(x_1)}{(\phi'(x_1))^2} dx_1$$

Assume that

$$|y_1| \leq c_0 d \quad |z_1| \leq c_0 d \quad h \leq y_2, z_2 \leq c_1 h \quad d \leq c_2 h$$

where  $0 < c_0 < 1$ . Let define  $0 < \theta_y, \theta_z < \pi$  such that

$$\cos \theta_y = \frac{x_1 - y_1}{((x_1 - y_1)^2 + y_2^2)^{1/2}}$$

$$\cos \theta_z = \frac{x_1 - z_1}{((x_1 - z_1)^2 + z_2^2)^{1/2}}$$

By mean value theorem and the law of sines, we get

$$\begin{aligned}
|\phi'(x_1)| &= |\cos \theta_z - \cos \theta_y| = |\sin \theta'| |\theta_z - \theta_y| \\
&\geq \frac{h}{(1+c_0)d} |\sin(\theta_z - \theta_y)| \\
&= \frac{h}{(1+c_0)d} \frac{|z-y|}{|x-y|} \sin \theta_{|x-y|} \\
&= \frac{h}{(1+c_0)d} \frac{|z-y|}{|x-z|} \sin \theta_{|x-z|} \\
&\geq \frac{h^2}{(1+c_0)^2 d^2} \frac{|z-y|}{|x-y|} \\
\text{or} \quad &\geq \frac{h^2}{(1+c_0)^2 d^2} \frac{|z-y|}{|x-z|}
\end{aligned}$$

Then we have

$$\begin{aligned}
\left| \frac{g(x_1)}{\phi'(x_1)} \right| &\leq \frac{(1+c_0)^2 d^2}{h^2} \frac{1}{|z-y||x-y|^{1/2}|x-z|^{1/2}} \\
&\leq C \frac{d^2}{h^3} \frac{1}{|z-y|}
\end{aligned}$$

Moreover, by mean value theorem again, we have

$$\begin{aligned}
|\phi''(x_1)| &= \left| \frac{\sin^2 \theta_z}{|x-z|} - \frac{\sin^2 \theta_y}{|x-y|} \right| \\
&= \left| \frac{2 \sin \theta' \cos \theta'}{|x-y'|} (\theta_z - \theta_y) - \frac{\sin^2 \theta'}{|x-y'|^2} (|x-z| - |x-y|) \right| \\
&\leq \pi \frac{|\sin(\theta_z - \theta_y)|}{h} + \frac{|z-y|}{h^2} \\
&\leq \pi \frac{|\sin \theta_{|x-z|}| |z-y|}{h|x-z|} + \frac{|z-y|}{h^2} \\
&\leq C \frac{|z-y|}{h^2}
\end{aligned}$$

Now, it is easy to see that

$$\begin{aligned}
&\left| \int_{-d}^d \frac{g'(x_1)}{\phi'(x_1)} - \frac{g(x_1)\phi''(x_1)}{(\phi'(x_1))^2} dx_1 \right| \\
&\leq C \frac{d^3}{h^4} \frac{1}{|z-y|} + C \frac{d^3}{h^3} \frac{1}{|z-y|} \frac{d^2}{h^3}
\end{aligned}$$

Based on the above analysis, we can obtain

$$\left| \int_{-d}^d z_2 g(x_1) e^{i\phi(x_1)} \right| \leq C \left( \left( \frac{d}{h} \right)^2 + \left( \frac{d}{h} \right)^3 + \left( \frac{d}{h} \right)^5 \right) \frac{1}{|z-y|}$$

#### 4. 2017.11.08

$$\begin{aligned}
\sin \phi_\kappa - \sin(t + \phi) &= -2 \cos\left(\frac{\phi_\kappa + \phi + t}{2}\right) \sin\left(\frac{t + \phi - \phi_\kappa}{2}\right) \\
\sin\left(\frac{t + \phi - \phi_\kappa}{2}\right) &= \sin \frac{t}{2} \cos\left(\frac{\phi - \phi_\kappa}{2}\right) + \cos \frac{t}{2} \sin\left(\frac{\phi - \phi_\kappa}{2}\right)
\end{aligned}$$

Some think, substituting  $t = 2 \arcsin s/2$  into following integral

$$\begin{aligned} & \int_0^\infty \chi(t)(\sin \phi_\kappa - \sin(t + \phi))^{1/2} e^{-i\rho \cos t} \\ &= \int_0^\infty \chi(t(s))(-s \cos(\frac{\phi - \phi_\kappa}{2}) - \sqrt{4 - s^2} \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2} e^{-i\rho s^2/2} \\ &= \int_0^\infty \chi(t)(-\sqrt{t} \cos(\frac{\phi - \phi_\kappa}{2}) - \sqrt{4 - t} \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2} t^{-1/2} e^{-i\rho t/2} \end{aligned}$$

Let

$$\begin{aligned} f(t) &= t^{-1/2} e^{-i\rho t/2} \\ g(t) &= - \int_t^{t-i\infty} x^{-1/2} e^{-i\rho x/2} dx \\ &= i \int_0^\infty (t - ix)^{-1/2} e^{-i\rho t - \rho x} dx \end{aligned}$$

It is easy to see that  $g'(t) = f(t)$ . Then we have

$$\begin{aligned} &= \int_0^\infty \chi(t)(-\sqrt{t} \cos(\frac{\phi - \phi_\kappa}{2}) - \sqrt{4 - t} \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2} t^{-1/2} e^{-i\rho t/2} \\ &= \chi(0)(-2 \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2} g(0) \\ &\quad - \int_0^\infty (\chi(t)(-\sqrt{t} \cos(\frac{\phi - \phi_\kappa}{2}) - \sqrt{4 - t} \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2})' g(t) dt \end{aligned}$$

We get

$$\begin{aligned} g(x) &= \int_0^\infty \chi(t)(-\sqrt{t} \cos(\frac{\phi - \phi_\kappa}{2}) - \sqrt{4 - t} \sin(\frac{\phi - \phi_\kappa}{2}))^{1/2} t^{-1/2} (t - ix)^{-1/2} e^{-i\rho t} dt \\ R(\rho) &= \int_0^\infty g(x) e^{-\rho x} dx \end{aligned}$$

Because  $\chi(t)$  has compact support  $(-\delta, \delta)$ , we obtain

$$gg(x) = \int_0^\delta (\sqrt{t} \cos(\theta) - \sqrt{4 - t} \sin \theta)^{-1/2} t^{-1/2} (t^2 + x^2)^{-1/4} dt$$

where  $\theta = \frac{\phi - \phi_\kappa}{2}$ . For  $x > 0$ , Put  $L(x)$ :

$$\begin{aligned} & \int_0^a \frac{1}{t^{3/4}} \frac{1}{(t^2 + x^2)^{1/4}} dt \\ &= 4 \int_0^a \frac{1}{(t^2 + x^2)^{1/4}} dt^{1/4} \\ &= 4 \int_0^{a^{1/4}} \frac{1}{(t^8 + x^2)^{1/4}} dt \\ &= 4x^{-1/4} \int_0^{(\frac{a}{x})^{1/4}} \frac{1}{(t^8 + 1)^{1/4}} dt \\ &= 4x^{-1/4} \int_0^{(\frac{a}{x})^{1/4}} \frac{1}{(t^8 + 1)^{1/4}} dt \\ &\leq 4x^{-1/4} \int_0^\infty \frac{1}{(t^8 + 1)^{1/4}} dt \end{aligned}$$

Back to analysis  $gg(x)$ , we have

$$\begin{aligned}
gg(x) &\leq \int_0^\delta \left| \frac{\sqrt{t} + 2|\sin \theta|}{t - 4\sin^2 \theta} \right|^{1/2} t^{-1/2} (t^2 + x^2)^{-1/4} dt \\
&= \int_0^\delta \left| \frac{1}{\sqrt{t} - 2|\sin \theta|} \right|^{1/2} t^{-1/2} (t^2 + x^2)^{-1/4} dt \\
&= 2 \int_0^{\sqrt{\delta}} \left| \frac{1}{t - 2|\sin \theta|} \right|^{1/2} (t^4 + x^2)^{-1/4} dt \\
&= 2 \int_{-2|\sin \theta|}^{\sqrt{\delta} - 2|\sin \theta|} |t|^{-1/2} ((t + 2|\sin \theta|)^4 + x^2)^{-1/4} dt \\
&\leq 4 \int_0^{\delta^{1/4}} (t^8 + x^2)^{-1/4} dt + 4 \int_0^{\sqrt{2|\sin \theta|}} ((t^2 - 2|\sin \theta|)^4 + x^2)^{-1/4} dt \\
&\leq Cx^{-1/4} (1 + \int_0^{\sqrt{2|\sin \theta|}} ((t^2 - 2|\sin \theta|)^4/x + x)^{-1/4} dt) \\
&\leq Cx^{-1/4} (1 + \int_0^{\sqrt{2|\sin \theta|}} (t^2 - 2|\sin \theta|)^{-1/2} dt) \\
&= Cx^{-1/4} (1 + \int_0^1 (1 - t^2)^{-1/2} dt) \leq Cx^{-1/4}
\end{aligned}$$

Immediately, we can obtain

$$|g(x)| \leq Cx^{-1/4}$$

It follows that

$$R(\rho) \leq \int_0^\infty x^{-1/4} e^{-\rho x} \leq C\rho^{-3/4}$$

## 5. stationary of phase lemma

**Lemma 5.1** Assume that  $0 < \kappa := \sin \phi_\kappa < 1$ ,  $0 < \phi_\kappa < \pi/2$ ,  $0 \leq \phi \leq \pi/2$ . Let

$$f(t, \phi) := F(\sin(t + \phi), \cos(t + \phi), (\kappa^2 - \sin^2(t + \phi))^{1/2}) \quad (5.1)$$

be a complexed function in  $C([-\pi/2, \pi/2] \times [0, \pi/2])$ . Moreover, its partial derivative with respect to  $t$  can be represented as

$$\frac{\partial f(t, \phi)}{\partial t} = g(t, \phi) (\kappa^2 - \sin^2(t + \phi))^{-1/2} \quad (5.2)$$

where  $g(t, \phi)$  is uniformly bounded. Then for any  $\rho \geq 1$ , we have

$$\begin{aligned}
&\left| I(\rho, \phi) := \int_{-\pi/2}^{\pi/2} f(t) e^{i\rho \cos t} dt - \left( \frac{2\pi}{\rho} \right)^{1/2} f(0) e^{i\rho - i\pi/4} \right| \\
&\leq C \frac{1}{\rho^{3/4}}
\end{aligned} \quad (5.3)$$

**Proof.** Solving the following equation:

$$\kappa^2 - \sin^2(t + \phi) = 0$$

we have, if  $0 < \phi < \pi/2 - \phi_\kappa$ ,

$$t_1(\phi) = \phi_\kappa - \phi \quad t_2(\phi) = -\phi_\kappa - \phi$$

and if  $\pi/2 - \phi_\kappa \leq \phi < \pi/2$ ,

$$t_1(\phi) = \phi_\kappa - \phi \quad t_2(\phi) = \pi - \phi_\kappa - \phi$$

Since  $|t_2(\phi)| < \phi_\kappa$  or  $|t_2(\phi)| < \pi/2 - \phi_\kappa$ , we now define  $\delta := \min(\frac{\phi_\kappa}{2}, \frac{\pi/2 - \phi_\kappa}{2})$  and it is easy to see that

$$\kappa + \sin(t + \phi) \neq 0 \quad (5.4)$$

$$\cos\left(\frac{t + \phi + \phi_\kappa}{2}\right) \neq 0 \quad (5.5)$$

for any  $(t, \phi) \in [-\delta, \delta] \times [0, \pi/2]$ . Let  $\chi_\delta \in C_0^\infty(-\pi/2, \pi/2)$  be the cut-off function with that  $0 \leq \chi_\delta \leq 1$ ,  $\chi_\delta = 1$  in  $(-\delta/2, \delta/2)$  and  $\chi_\delta = 0$  in  $(-\pi/2, \pi/2) \setminus (-\delta, \delta)$ . Then we can divide  $I$  into two parts such that

$$\begin{aligned} I &= \int_{-\delta}^{\delta} f(t) \chi_\delta(t) e^{i\rho \cos t} dt + \int_{-\pi/2}^{\pi/2} f(t) (1 - \chi_\delta(t)) e^{i\rho \cos t} dt \\ &=: I_1 + I_2 \end{aligned}$$

Substituting  $t(s) = 2 \arcsin s/2$  for  $t$  in  $I_1$ , we can obtain

$$I_1 = \int_{-2 \sin \frac{\delta}{2}}^{2 \sin \frac{\delta}{2}} f(t(s)) \chi_\delta(t(s)) \frac{1}{\sqrt{1 - s^2/4}} e^{i\rho} e^{-i\rho s^2/2} ds \quad (5.6)$$

$$= \int_0^{2 \sin \frac{\delta}{2}} (f(t(s)) \chi_\delta(t(s)) + f(-t(s)) \chi_\delta(-t(s))) \frac{1}{\sqrt{1 - s^2/4}} e^{i\rho} e^{-i\rho s^2/2} ds \quad (5.7)$$

$$:= I_{11} + I_{12} \quad (5.8)$$

Taking substitution  $s = \sqrt{x}$ , we get

$$I_{11} = \frac{1}{2} \int_0^{(2 \sin \frac{\delta}{2})^2} f(t(\sqrt{x})) \chi_\delta(t(\sqrt{x})) \frac{1}{\sqrt{1 - x/4}} x^{-1/2} e^{i\rho} e^{-i\rho x/2} dx$$

Observe that

$$\begin{aligned} \sin \phi_\kappa - \sin(t + \phi) &= -2 \cos\left(\frac{\phi_\kappa + \phi + t}{2}\right) \sin\left(\frac{t + \phi - \phi_\kappa}{2}\right) \\ \sin\left(\frac{t + \phi - \phi_\kappa}{2}\right) &= \sin \frac{t}{2} \cos\left(\frac{\phi - \phi_\kappa}{2}\right) + \cos \frac{t}{2} \sin\left(\frac{\phi - \phi_\kappa}{2}\right) \\ &:= \sin \frac{t}{2} \cos \theta + \cos \frac{t}{2} \sin \theta \end{aligned}$$

where  $\theta = \frac{\phi - \phi_\kappa}{2}$ . By lemma (1.3) and using representation (5.2), inequality (5.4-5.5), it follows that

$$\begin{aligned} &|I_{11} - \frac{1}{2} \sqrt{\frac{2\pi}{\rho}} f(0) e^{i\rho - i\frac{\pi}{4}}| \\ &\leq \int_0^\infty e^{-\rho y} dy \int_0^{(2 \sin \frac{\delta}{2})^2} \left| \frac{\partial(f(t(\sqrt{x})) \chi_\delta(t(\sqrt{x})) \frac{1}{\sqrt{1 - x/4}})}{\partial x} \right| (x^2 + y^2)^{-\frac{1}{4}} dx \end{aligned}$$

$$\begin{aligned}
&\leq C \int_0^\infty e^{-\rho y} dy \int_0^{(2 \sin \frac{\delta}{2})^2} |\sqrt{x} \cos \theta + \sqrt{4-x} \sin \theta|^{-1/2} x^{-1/2} (x^2 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \int_0^{(2 \sin \frac{\delta}{2})^2} \frac{(\sqrt{x} |\cos \theta| + \sqrt{4-x} |\sin \theta|)^{1/2}}{|x - 4 \sin^2 \theta|^{1/2}} x^{-1/2} (x^2 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \int_0^{(2 \sin \frac{\delta}{2})^2} \frac{1}{|\sqrt{x} - 2 |\sin \theta||^{1/2}} x^{-1/2} (x^2 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \int_0^{2 \sin \frac{\delta}{2}} \frac{1}{|x - 2 \sin |\theta||^{1/2}} (x^4 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \int_{-2 \sin |\theta|}^{2 \sin \frac{\delta}{2} - 2 \sin |\theta|} \frac{1}{|x|^{1/2}} ((x + 2 \sin |\theta|)^4 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \int_{-2 \sin |\theta|}^{2 \sin \frac{\delta}{2}} \frac{1}{|x|^{1/2}} ((x + 2 \sin |\theta|)^4 + y^2)^{-\frac{1}{4}} dx \\
&\leq C \int_0^\infty e^{-\rho y} dy \left( \int_0^{\sqrt{2 \sin \frac{\delta}{2}}} (x^8 + y^2)^{-\frac{1}{4}} dx + \int_0^{\sqrt{2 \sin |\theta|}} ((x^2 - 2 \sin |\theta|)^4 + y^2)^{-\frac{1}{4}} dx \right) \\
&\leq C \int_0^\infty e^{-\rho y} dy \left( y^{-\frac{1}{4}} \int_0^\infty (x^8 + 1)^{-\frac{1}{4}} dx + y^{-\frac{1}{4}} \int_0^{\sqrt{2 \sin |\theta|}} (2 \sin |\theta| - x^2)^{-\frac{1}{2}} dx \right) \\
&\leq C \int_0^\infty y^{-\frac{1}{4}} e^{-\rho y} dy \left( \int_0^\infty (x^8 + 1)^{-\frac{1}{4}} dx + \int_0^1 (1 - x^2)^{-\frac{1}{2}} dx \right) \leq C \frac{1}{\rho^{3/4}}
\end{aligned}$$

Using the same argument, we can also carry out

$$|I_{12} - \frac{1}{2} \sqrt{\frac{2\pi}{\rho}} f(0) e^{i\rho - i\frac{\pi}{4}}| \leq C \frac{1}{\rho^{3/4}} \quad (5.9)$$

It remains to estimate  $I_2$ . Note that there exists  $m > 0$  such that  $|\sin t| \geq m$  for any  $t \in [-\pi/2, \pi/2] \setminus (-\delta/2, \delta/2)$ . Upon integration by parts and representation (5.2) again, we have

$$\begin{aligned}
|I_{12}| &\leq C \rho^{-1} \left( 1 + \left| \int_{[-\pi/2, \pi/2] \setminus (-\delta/2, \delta/2)} \frac{\partial(f(t)(1 - \chi_\delta(t)))}{\partial t} \frac{1}{\sin t} dt \right| \right) \\
&\leq C \rho^{-1} \left( 1 + \int_{-\pi/2}^{\pi/2} \left| \frac{\partial(f(t)(1 - \chi_\delta(t)))}{\partial t} \right| dt \right) \\
&\leq C \rho^{-1} \left( 1 + \int_{-\pi/2}^{\pi/2} |(\kappa^2 - \sin^2(t + \phi))^{-1/2}| dt \right) \\
&\leq C \rho^{-1} \left( 1 + \int_{-\pi/2}^{\pi/2} |(\kappa^2 - \sin^2 t)^{-1/2}| dt \right) \\
&\leq C \rho^{-1}
\end{aligned}$$

This completes the proof.  $\square$



## 6. cross term of psf, 17.11.15

We need the following slight generalization of Van der Corput lemma for the oscillatory integral [3, P.152].

**Lemma 6.1** *Let  $-\infty < a < b < \infty$ , and  $u$  is a  $C^k$  function  $u$  in  $(a, b)$ .*

1. *If  $|u'(t)| \geq 1$  for  $t \in (a, b)$  and  $u'$  is monotone in  $(a, b)$ , then for any  $\phi(t)$  in  $(a, b)$  with integrable derivatives*

$$\left| \int_a^b e^{i\lambda u(t)} \phi(t) dt \right| \leq 3\lambda^{-1} \left[ |\phi(b)| + \int_a^b |\phi'(t)| dt \right].$$

2. *For all  $k \geq 2$ , if  $|u^{(k)}(t)| \geq 1$  for  $t \in (a, b)$ , then for any  $\phi(t)$  in  $(a, b)$  with integrable derivatives*

$$\left| \int_a^b e^{i\lambda u(t)} \phi(t) dt \right| \leq 12k\lambda^{-1/k} \left[ |\phi(b)| + \int_a^b |\phi'(t)| dt \right].$$

**Proof.** The assertion can be proved by extending the Van der Corput lemma in [3]. Here we omit the details.  $\square$

**Lemma 6.2** *For  $0 < \kappa < 1$ , let  $F(\lambda) = \int_0^\kappa f(t) e^{i\lambda(\sqrt{1-t^2} - \tau\sqrt{\kappa^2-t^2} + \alpha t)} dt$ , where  $\tau \geq c_0 > 0$  and  $\alpha \in \mathbb{R}$ , then we have*

$$|F(\lambda)| \leq C(\kappa) \lambda^{-\frac{1}{2N_*}} \left[ |f(\kappa)| + \int_0^\kappa |f'(t)| dt \right]$$

where  $N_* = \min\{N | \kappa^{2N-1} < c_0, N \in \mathbb{Z}_+\}$ .

**Proof.** Put  $\phi(t) = -\sqrt{1-t^2}$  and  $\psi(t, \tau) = \tau\phi(t/\kappa) - \phi(t) + \alpha t$ . For easy of notations, we denote the  $n$ -th partial derivative of  $g(t)$  with respect to  $t$  by  $g^{(n)}(t)$ . Then, it is to see that, for  $n > 1$

$$\psi^{(n)}(t, \tau) = \frac{\tau}{\kappa^{n-1}} \phi^{(n)}\left(\frac{t}{\kappa}\right) - \phi^{(n)}(t)$$

A standard computation show that

$$\begin{aligned} \phi^{(1)}(t) &= \frac{t}{\sqrt{1-t^2}} \\ \phi^{(2)}(t) &= \frac{1}{(1-t^2)^{3/2}} \\ \phi^{(3)}(t) &= \frac{3t}{(1-t^2)^{5/2}} \end{aligned}$$

Moreover, for  $n \geq 3$ , we have

$$\phi^{(n)}(t) = \frac{p_n(t)}{(1-t^2)^{n-1/2}} \tag{6.1}$$

where  $p_n = \sum_0^{n-2} a_k^n t^k$  is a  $(n-2)$ -th polynomial such that its coefficients satisfy the following recursion formula:

$$\begin{aligned} a_{n-1}^{n+1} &= (n+1)a_{n-2}^n, & a_{n-2}^{n+1} &= (n+2)a_{n-3}^n \\ a_k^{n+1} &= (k+1)a_{k+1}^n + (2n-k)a_{k-1}^n & \text{for } 1 \leq k \leq n-3 \\ a_0^{n+1} &= a_1^n \end{aligned}$$

Since the polynomial coefficients are all positive, it is obvious that for  $n \geq 1$ ,  $\phi^{(n)}(t)$  is a monotone increasing positive function. Using the recursion formula, it follows that

$$\phi^{(n)}(0) = \begin{cases} 0 & n \text{ is odd,} \\ (n-1)!!(n-3)!! & n \text{ is even.} \end{cases} \quad (6.2)$$

where  $(2k-1)!!$  is double factorial and  $n > 3$ . We are now in the position to proof the inequality. Since  $0 < \kappa < 1$ , obersev that

$$\psi^{(2N_*+1)}(t, \tau) \geq \frac{\tau}{\kappa^{2N_*}} \phi^{(2N_*+1)}(t) - \phi^{(2N_*+1)}(t) > 0$$

Therefore,  $\psi^{(2N_*)}(t, \tau)$  is monotone increasing in  $[0, \kappa)$ . By (6.2), we get

$$\psi^{(2N_*)}(t, \tau) \geq \psi^{(2N_*)}(0, \tau) \geq \psi^{(2N_*)}(0, c_0) = C(2N_*) \left( \frac{c_0}{\kappa^{2N_*-1}} - 1 \right) > 0 \quad (6.3)$$

The lemma is now a direct consequence of lemma (6.1).  $\square$

## 7. Other exponential decay term: 17.11.16 on G1

The parameterization of hyperbolic curve passing  $(\pm 1, 0)$  is:

$$\xi_1 = \pm \sqrt{t^2 + 1} \quad \xi_2 = t$$

where  $t \in \mathbb{R}$ . Substituting  $\xi = \xi_1 + \mathbf{i}\xi_2$  into  $\mu(\xi) := (1 - \xi^2)^{1/2}$  and  $\mu_\kappa(\xi) := (\kappa^2 - \xi^2)^{1/2}$ , we get

$$\begin{aligned} \text{Im } \mu(\xi) &= \text{Im} (1 - (\xi_1^2 - \xi_2^2 + \mathbf{i}2\xi_1\xi_2))^{1/2} \\ &= \text{Im} (-2t\sqrt{t^2 + 1}\mathbf{i})^{1/2} = t^{1/2}(t^2 + 1)^{1/4} \end{aligned}$$

$$\begin{aligned} \text{Im } \mu_\kappa(\xi) &= \text{Im} (\kappa^2 - (\xi_1^2 - \xi_2^2 + \mathbf{i}2\xi_1\xi_2))^{1/2} \\ &= \text{Im} (\kappa^2 - 1 - 2t\sqrt{t^2 + 1}\mathbf{i})^{1/2} \\ &= \sqrt{\frac{\sqrt{(1 - \kappa^2)^2 + 4t(t^2 + 1)} + 1 - \kappa^2}{2}} \\ &\geq t^{1/2}(t^2 + 1)^{1/4} \end{aligned}$$

where we only consider the branch, denoted by  $\Gamma^+$ , in the first quadrant here. For  $a > 0, b > 0$ , we have

$$|e^{\mathbf{i}\xi a + \mathbf{i}\mu(\xi)b + \mathbf{i}\mu_\kappa(\xi)c}| \leq e^{-ta - t^{1/2}(t^2 + 1)^{1/4}b - t^{1/2}(t^2 + 1)^{1/4}c} \leq e^{-t(b+c)}$$

**Lemma 7.1** For  $\xi \in \Gamma_0$ , let  $f(\xi)$  is a complex valued function in  $L^1(\Gamma^+)$  such that  $|f(\xi)| \leq C(1 + \xi^k)$ ,  $k \in \mathbb{Z}_+$ . Then we have

$$\begin{aligned} |I(a, b, c) &:= \int_{\Gamma^+} f(\xi) e^{\mathbf{i}\xi a + \mathbf{i}\mu(\xi)b + \mathbf{i}\mu_\kappa(\xi)c} d\xi| \\ &\leq C \left( \frac{1}{b+c} + \frac{1}{(b+c)^k} \right) \end{aligned}$$

**Proof.**

$$\frac{d\xi(t)}{dt} = \frac{t}{\sqrt{t^2 + 1}} + \mathbf{i}$$

Substituting  $\xi(t)$  into  $I(a, b, c)$ , we have

$$\begin{aligned} |I(a, b, c)| &= \left| \int_0^\infty |f(\xi(t))| \frac{d\xi(t)}{dt} e^{\mathbf{i}\xi(t)a + \mathbf{i}\mu(\xi(t))b + \mathbf{i}\mu_\kappa(\xi(t))c} dt \right| \\ &\leq C \int_0^\infty (1 + t^k) e^{-t(b+c)} dt \\ &\leq C \left( \frac{1}{b+c} + \frac{1}{(b+c)^k} \right) \end{aligned}$$

□

**Lemma 7.2** *Let  $f(\xi)$  is a bounded complex valued function in  $L^1((\kappa, 1))$ . Then we have*

$$\begin{aligned} |I(a, b)| &:= \int_\kappa^1 |f(\xi)| e^{\mathbf{i}\xi a + \mathbf{i}\mu_\kappa(\xi)b} d\xi \\ &\leq C \frac{1}{b} \end{aligned}$$

**Proof.** It is simple to see that

$$\begin{aligned} |I(a, b)| &\leq C \int_\kappa^1 e^{-b\sqrt{\xi^2 - \kappa^2}} d\xi \\ &\leq C \int_0^{\sqrt{1-\kappa^2}} \frac{t}{\sqrt{t^2 + \kappa^2}} e^{-bt} dt \\ &\leq C \frac{1}{b} \end{aligned}$$

□

## 8. about principle of arguement

Put

$$\begin{aligned} \delta_\pm(t) &= (\kappa - 2t^2)^2 \mp \mathbf{i}4t^2\sqrt{1-t^2}\sqrt{t^2-\kappa} \\ &:= f_1(t) \mp \mathbf{i}f_2(t) \end{aligned}$$

where  $0 < \kappa < 1$  and we have

$$\delta'_\pm(t) = f'_1(t) \mp \mathbf{i}f'_2(t)$$

It is easy to see  $f_2(1) = f_2(\kappa) = 0$  and  $f_1(t) > 0$  for any  $\kappa \leq t \leq 1$ . Then

$$\begin{aligned} &\int_\kappa^1 \frac{\delta'_+(t)}{\delta_+(t)} - \frac{\delta'_-(t)}{\delta_-(t)} dt \\ &= 2\mathbf{i} \int_\kappa^1 \operatorname{Im} \left( \frac{\delta'_+(t)}{\delta_+(t)} \right) dt \end{aligned}$$

$$\begin{aligned}
&= 2\mathbf{i} \int_{\kappa}^1 \operatorname{Im} \frac{(f_1'(t) - \mathbf{i}f_2'(t))f_1(t) + \mathbf{i}f_2(t)}{(f_1(t) - \mathbf{i}f_2(t))(f_1(t) + \mathbf{i}f_2(t))} dt \\
&= 2\mathbf{i} \int_{\kappa}^1 \frac{f_1'(t)f_2(t) - f_1(t)f_2'(t)}{f_1^2(t) + f_2^2(t)} dt \\
&= 2\mathbf{i} \int_{\kappa}^1 \frac{f_1^2(t)}{f_1^2(t) + f_2^2(t)} \frac{f_1'(t)f_2(t) - f_1(t)f_2'(t)}{f_1^2(t)} dt \\
&= -2\mathbf{i} \int_{\kappa}^1 \frac{f_1^2(t)}{f_1^2(t) + f_2^2(t)} d \frac{f_2(t)}{f_1(t)} \\
&= -2\mathbf{i} \arctan \frac{f_2(t)}{f_1(t)} \Big|_{\kappa}^1 = 0
\end{aligned}$$

Notic that, the condition only used above are  $f_2(1) = f_2(\kappa) = 0$  and  $f_1(t) > 0$ .

## 9. Fundamental solution of Elastic wave

$$G(x; y) = \frac{1}{\omega^2} (\nabla \times \nabla \cdot (g_s(x; y)\mathbb{I}) - \nabla \nabla g_p(x; y)) \quad (9.1)$$

$$= \frac{1}{\omega^2} (k_s^2 g_s(x, y) + \nabla \nabla (g_s(x; y) - g_p(x; y))) \quad (9.2)$$

where  $y$  is the Dirac source,  $g_p(x; y)$  or  $g_s(x; y)$  is the fundamental solution of the scalar Helmholtz equation with wavenumbers  $k_p = \omega/c_p$  or  $k_s = \omega/c_s$ .

$$g_{\alpha} = \frac{\mathbf{i}}{4} H_0^{(1)}(k_{\alpha}|x - y|) \quad (9.3)$$

where  $H_0^{(1)}(t)$  is the Hankel function of the first type and order zero. By straight calculation using  $H_1^{(1)}(t) = -dH_0^{(1)}(t)/dt$  and  $dH_1^{(1)}(t)/dt = H_0^{(1)}(t) - H_1^{(1)}(t)/t$ , we have

$$\begin{aligned}
G_{ij}(x; y) &= \frac{\mathbf{i}}{4} \left\{ \left( \frac{k_s^2}{\omega^2} H_0^{(1)}(k_s|x - y|) - \frac{1}{\omega^2} \frac{k_s H_1^{(1)}(k_s|x - y| - k_p H_1^{(1)}(k_p|x - y|)}{|x - y|} \right) \delta_{ij} \right. \\
&\quad \left. + \frac{1}{\omega^2} \left[ \left( \frac{2k_s H_1^{(1)}(k_s|x - y| - 2k_p H_1^{(1)}(k_p|x - y|)}{|x - y|} - (k_s^2 H_0^{(1)}(k_s|x - y|) - k_p^2 H_0^{(1)}(k_p|x - y|)) \right) \frac{(x_i - y_i)(x_j - y_j)}{|x - y|^2} \right] \right\}
\end{aligned}$$

The definition of hankal function is  $H_k^{(1)}(t) = J_k(t) + \mathbf{i}Y_k(t)$  where

$$J_k(t) = \sum_{p=0}^{\infty} \frac{(-1)^p}{p!(k+p)!} (t/2)^{k+2p}$$

Specially

$$\begin{aligned}
J_0(t) &= \sum_{p=0}^{\infty} \frac{(-1)^p}{p!p!} (t/2)^{2p} = 1 + \dots \\
J_1(t) &= \sum_{p=0}^{\infty} \frac{(-1)^p}{p!(1+p)!} (t/2)^{1+2p} = \frac{t}{2} + \dots
\end{aligned}$$

and

$$Y_k(t) = \frac{1}{\pi} \{ \ln t^2 - 2 \ln 2 + 2C_{euler} \} J_k(t) - \frac{1}{\pi} \sum_{p=0}^{k-1} \frac{(k-1-p)!}{p!} (2/t)^{k-2p} \\ - \frac{1}{\pi} \sum_{p=0}^{\infty} \frac{(-1)^p}{p!(k+p)!} (t/2)^{k+2p} \{ \psi(p+k) + \psi(p) \}$$

Speceilly

$$Y_0(t) = \frac{1}{\pi} \{ \ln t^2 - 2 \ln 2 + 2C_{euler} \} J_0(t) - \frac{1}{\pi} \sum_{p=1}^{\infty} \frac{(-1)^p}{p!p!} (t/2)^{2p} \{ 2\psi(p) \} \\ Y_1(t) = \frac{1}{\pi} \{ \ln t^2 - 2 \ln 2 + 2C_{euler} \} J_1(t) - \frac{1}{\pi} \frac{2}{t} - \frac{t}{2\pi} \\ - \frac{1}{\pi} \sum_{p=1}^{\infty} \frac{(-1)^p}{p!(1+p)!} (t/2)^{1+2p} \{ \psi(p+1) + \psi(p) \}$$

Thus, we have

$$H_0^{(1)}(kr) = 1 + \mathbf{i} \frac{2}{\pi} (C_{euler} + \ln k - \ln 2) + \mathbf{i} \frac{1}{\pi} \ln r^2 + o(kr) \\ H_1^{(1)}(kr) = \frac{kr}{2} + \mathbf{i} \frac{1}{\pi} (C_{euler} + \ln k - \ln 2 - \frac{1}{2}) kr - \mathbf{i} \frac{1}{\pi} \frac{2}{kr} + \mathbf{i} \frac{1}{\pi} \ln r^2 \frac{kr}{2} + o(k^2 r^2) \\ \frac{\mathbf{i}}{4} H_0^{(1)}(kr) = \frac{\mathbf{i}}{4} - \frac{1}{2\pi} (C_{euler} + \ln k - \ln 2) - \frac{1}{4\pi} \ln r^2 + o(kr) \\ \frac{\mathbf{i}}{4} H_1^{(1)}(kr) = \mathbf{i} \frac{kr}{8} - \frac{1}{4\pi} (C_{euler} + \ln k - \ln 2 - \frac{1}{2}) kr + \frac{1}{4\pi} \frac{2}{kr} - \frac{1}{4\pi} \ln r^2 \frac{kr}{2} + o(k^2 r^2)$$

We also need to define the surface traction  $T_x^n(\cdot)$  on the normal direction  $\mathbf{n}$ ,

$$T_x^n u(x) := \sigma \cdot \mathbf{n} = 2\mu \frac{\partial u}{\partial n} + \lambda n \operatorname{div} u + \mu \mathbf{n} \times \operatorname{curl} u$$

where

$$\sigma(u) = \begin{pmatrix} (\lambda + 2\mu) \partial u_1 / \partial x_1 + \lambda \partial u_2 / \partial x_2 & \mu \partial u_1 / \partial x_2 + \mu \partial u_2 / \partial x_1 \\ \mu \partial u_1 / \partial x_2 + \mu \partial u_2 / \partial x_1 & (\lambda + 2\mu) \partial u_2 / \partial x_2 + \lambda \partial u_1 / \partial x_1 \end{pmatrix}$$

A simple computation show that

$$\frac{\partial^3 H_0^{(1)}(k|x-y|)}{\partial x_i^2 \partial x_j} = (1 + 2\delta_{ij})(-k^2 H_0^{(1)}(kr) \frac{r_j}{r^2} + 2k H_1^{(1)}(kr) \frac{r_j}{r^3}) \\ + k^3 H_1^{(1)}(kr) \frac{r_i^2 r_j}{r^3} + 4k^2 H_0^{(1)}(kr) \frac{r_i^2 r_j}{r^4} - 8k H_1^{(1)}(kr) \frac{r_i^2 r_j}{r^5}$$

where  $r = |x - y|$  and  $r_i = x_i - y_i$ .

$$\frac{\mathbf{i}}{4} H_0^{(1)}(kr) = -\frac{1}{2\pi} (\ln \frac{kr}{2} + C_{euler}) (1 - (\frac{kr}{2})^2 + \dots) + \frac{1}{4\pi} (2(\frac{kr}{2})^2 + \dots) + \frac{\mathbf{i}}{4} (1 - (\frac{kr}{2})^2 + \dots) \\ = -\frac{1}{2\pi} (\ln \frac{kr}{2}) (1 + O(r^2)) - \frac{1}{2\pi} C_{euler} + \frac{\mathbf{i}}{4} + O(r^2) \\ \frac{\mathbf{i}}{4} H_1^{(1)}(kr) = -\frac{1}{2\pi} (\ln \frac{kr}{2} + C_{euler}) (\frac{kr}{2} - \frac{1}{2} (\frac{kr}{2})^3 + \dots) + \frac{1}{4\pi} (\frac{kr}{2} + O(r^3)) + \frac{\mathbf{i}}{4} (\frac{kr}{2} - \frac{1}{2} (\frac{kr}{2})^3 + \dots) + \frac{1}{2\pi} \frac{1}{kr} \\ = -\frac{1}{4\pi} (\ln \frac{kr}{2}) (kr + O(r^3)) - \frac{kr}{4\pi} C_{euler} + \frac{kr}{8\pi} + \frac{\mathbf{i}kr}{8} + \frac{1}{2\pi} \frac{1}{kr} + O(r^3)$$

$$A(kr) := \frac{\mathbf{i}}{4}(k^2 H_0^{(1)}(kr) - 2k H_1^{(1)}(kr)/r) = \frac{k^2}{4\pi}(\ln \frac{kr}{2})(\frac{kr}{2})^2 - \frac{1}{\pi r^2} - \frac{k^2}{4\pi} + O(r^2)$$

and

$$A_{sp}(r) = A(k_s r) - A(k_p r) = \frac{k_s^2}{4\pi}(\ln \frac{kr}{2})(\frac{kr}{2})^2 - \frac{k_p^2}{4\pi}(\ln \frac{kr}{2})(\frac{kr}{2})^2 - (\frac{k_s^2}{4\pi} - \frac{k_p^2}{4\pi}) + O(r^2)$$

Let  $g^{jkk} = \frac{\partial^3 g}{\partial x_j \partial x_k^2}$ ,  $d = g_s - g_p$ , thus

$$\begin{aligned} g^{ij} &= (1 + 2\delta_{ij})(-A(kr)\frac{r_j}{r^2}) + \frac{\mathbf{i}k^3}{4}H_1^{(1)}(kr)\frac{r_i^2 r_j}{r^3} + 4A(kr)\frac{r_i^2 r_j}{r^4} \\ &= (1 + 2\delta_{ij})(\frac{1}{\pi r^3} + \frac{k^2}{4\pi r})\frac{r_j}{r} - (\frac{4}{\pi r^3} + \frac{k^2}{2\pi r})\frac{r_i^2 r_j}{r^3} + O(r \ln r) \\ d^{ij} &= (1 + 2\delta_{ij})(-A_{sp}\frac{r_j}{r^2}) + (\frac{\mathbf{i}k_s^3}{4}H_1^{(1)}(k_s r) - \frac{\mathbf{i}k_p^3}{4}H_1^{(1)}(k_p r))\frac{r_i^2 r_j}{r^3} + 4A_{sp}\frac{r_i^2 r_j}{r^4} \\ &= (1 + 2\delta_{ij})(\frac{k_s^2}{4\pi r} - \frac{k_p^2}{4\pi r})\frac{r_j}{r} - (\frac{k_s^2}{2\pi r} - \frac{k_p^2}{2\pi r})\frac{r_i^2 r_j}{r^3} + O(r \ln r) \\ &= (1 + 2\delta_{ij})\frac{(\lambda + \mu)\omega^2}{\mu(\lambda + 2\mu)}\frac{1}{4\pi r}\frac{r_j}{r} - \frac{(\lambda + \mu)\omega^2}{\mu(\lambda + 2\mu)}\frac{1}{2\pi r}\frac{r_i^2 r_j}{r^3} + O(r \ln r) \\ k^2 g^i &= -\frac{\mathbf{i}}{4}H_1^{(1)}(kr)\frac{kr_i}{r} = -\frac{k^2}{2\pi r}\frac{r_i}{r} + O(r \ln r) \\ d^{ij} + d^{jjj} &= 2\frac{(\lambda + \mu)\omega^2}{\mu(\lambda + 2\mu)}\frac{1}{4\pi r}\frac{r_j}{r} + O(r \ln r) \end{aligned}$$

Then we have [5, p43]

$$\begin{aligned} \sigma(Ge_1)n &= \frac{1}{\omega^2} \begin{pmatrix} (\lambda + 2\mu)(k_s^2 g_s^1 + d^{111}) + \lambda d^{122} & \mu(k_s^2 g_s^2 + d^{112}) + \mu d^{112} \\ \mu(k_s^2 g_s^2 + d^{112}) + \mu d^{112} & (\lambda + 2\mu)d^{122} + \lambda(k_s^2 g_s^1 + d^{111}) \end{pmatrix} n \\ &= \frac{\mu}{2\pi(\lambda + 2\mu)} \left( \left( \frac{2(\lambda + \mu)r_1^2}{\mu r^2} + 1 \right) \left( -\frac{r_1 n_1}{r^2} - \frac{r_2 n_2}{r^2} \right) - \begin{pmatrix} 0 \\ \frac{r_2 n_1 - r_1 n_2}{r^2} \end{pmatrix} \right) + O(r \ln r) \end{aligned}$$

and

$$\begin{aligned} \sigma(Ge_2)n &= \frac{1}{\omega^2} \begin{pmatrix} (\lambda + 2\mu)d^{112} + \lambda(k_s^2 g_s^2 + d^{222}) & \mu(k_s^2 g_s^1 + d^{122}) + \mu d^{122} \\ \mu(k_s^2 g_s^1 + d^{122}) + \mu d^{122} & (\lambda + 2\mu)(k_s^2 g_s^2 + d^{222}) + \lambda d^{112} \end{pmatrix} n \\ &= \frac{\mu}{2\pi(\lambda + 2\mu)} \left( \left( \frac{2(\lambda + \mu)r_1 r_2}{\mu r^2} \right) \left( -\frac{r_1 n_1}{r^2} - \frac{r_2 n_2}{r^2} \right) - \begin{pmatrix} \frac{r_1 n_2 - r_2 n_1}{r^2} \\ 0 \end{pmatrix} \right) + O(r \ln r) \end{aligned}$$

Now Let  $u$  be represented as single potential:

$$u = \int_{\partial D} G(x, y) \phi(y) ds(y) \quad (9.4)$$

with Neumann boundary condition

$$T_x u(x) = f(x) \quad \text{on } \partial D \quad (9.5)$$

Then we obtain corresponding integral equation

$$\mathbf{P.V.} \int_{\partial D} T_x G(x, y) \phi(y) ds(y) - \frac{1}{2} \phi(x) = f(x) \quad (9.6)$$

where  $x \in \partial D$ . We describe the necessary parametrization of the integral equation in the two-dimensional case. We assume that the boundary curve  $\partial D$  possesses a regular analytic and  $2\pi$ -periodic parametric representation of the form

$$x(t) = (x_1(t), x_2(t))$$

in counterclockwise orientation satisfying  $|x'(t)| > 0$  for all  $t$ . Let [4]

$$\begin{aligned} T(x, y) &= (T_x(N_1(x, y))n, T_x(N_1(x, y))n) \\ T_0(x, y) &= -\frac{\mu}{2\pi(\lambda + 2\mu)} \begin{pmatrix} 0 & \frac{r_1 n_2 - r_2 n_1}{r^2} \\ \frac{r_2 n_1 - r_1 n_2}{r^2} & 0 \end{pmatrix} \\ T_1(x, y) &= T(x, y) - T_0(x, y) \end{aligned}$$

Then by above analysis we have

$$\int_0^{2\pi} T_1(x(t), x(\tau))\phi(x(\tau))|x'(\tau)|dt + \mathbf{P.V.} \int_0^{2\pi} T_0(x(t), x(\tau))\phi(x(\tau))|x'(\tau)|dt - \frac{1}{2}\phi(x(t)) = f(x(t))$$

In particular, using expansion above, we can deduce the diagonal terms:

$$\lim_{\tau \rightarrow t} \frac{-r_1 n_1 - r_2 n_2}{r^2} = \lim_{\tau \rightarrow t} \frac{(x_1(\tau) - x_1(t))x_2'(t) - (x_2(\tau) - x_2(t))x_1'(t)}{|x(t) - x(\tau)|^2|x'(t)|} = \frac{x_1''(t)x_2'(t) - x_2''(t)x_1'(t)}{2|x'(t)|^3}$$

and

$$\begin{aligned} &\lim_{\tau \rightarrow t} \frac{(r_1 n_2 - r_2 n_1)|x'(\tau)|(\tau - t)}{r^2} \\ &= \lim_{\tau \rightarrow t} \frac{(x_1(\tau) - x_1(t))x_1'(t) + (x_2(\tau) - x_2(t))x_2'(t))|x'(\tau)|(\tau - t)}{|x(t) - x(\tau)|^2|x'(t)|} = 1 \end{aligned}$$

According to above analysis, it is easy to see that  $T_1$  has no singularity. Therefore, the numerical formulation for  $T_1$  requires only straightforward application of simple quadrature formula. we choose an equidistant set of knots  $t_j := \pi j/n, j = 0, \dots, 2n-1$  and divide  $[0, 2\pi)$  into  $n$  equivalent interval  $I_i = [2j\pi/n, 2(j+1)\pi/n]$  where  $[0, 2\pi) = \bigcup_{j=1}^{j=n-1} I_i$ . Each  $I_i$  is described by 3 nodes of the intrinsic variable  $\xi (-1 \leq \xi \leq 1)$  and the

quadratic shape functions are:

$$\begin{aligned} A_{-1}(\xi) &= \frac{\xi(\xi - 1)}{2} \\ A_0(\xi) &= 1 - \xi^2 \\ A_1(\xi) &= \frac{\xi(\xi + 1)}{2} \end{aligned}$$

let

$$f(x, y) = \frac{(x_1 - y_1)n_2^x - (x_2 - y_2)n_1^x}{|x - y|^2}$$

and it is easy to see that  $(n_x^1, n_x^2) = (x_2'(t), -x_1'(t))/|x'(t)|$ . Now, we can represent the integral in variable  $\xi \in [-1, 1]$ . For  $x \in \partial D$  we have:

$$\begin{aligned} &\mathbf{P.V.} \int_{\partial D} f(x, y)\phi(y)ds(y) \\ &= \sum_{x \notin I_i} \int_{I_i} f(x, x(t))\phi(x(t))|x'(t)|dt + \mathbf{P.V.} \sum_{x \in I_i} \int_{I_i} f(x, x(t))\phi(x(t))|x'(t)|dt \end{aligned}$$

if  $x = x(2j\pi/n)$ , above integral becomes to

$$\begin{aligned}
& \sum_{i \neq j, j-1} \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{2j\pi}{n})) x'_k(\frac{2j\pi}{n})}{|x(\frac{2j\pi}{n}) - x^i(\xi)|^2} \phi(x^i(\xi)) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{2j\pi}{n})|} d\xi \\
& + \text{P.V.} \sum_{i=j, j-1} \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{2j\pi}{n})) x'_k(\frac{2j\pi}{n})}{|x(\frac{2j\pi}{n}) - x^i(\xi)|^2} \phi(x^i(\xi)) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{2j\pi}{n})|} d\xi \\
& \approx \sum_{i \neq j, j-1} \sum_{l=-1}^1 \phi(x^i(l)) \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{2j\pi}{n})) x'_k(\frac{2j\pi}{n})}{|x(\frac{2j\pi}{n}) - x^i(\xi)|^2} A_l(\xi) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{2j\pi}{n})|} d\xi \\
& + \phi(x(\frac{2j\pi}{n})) \text{P.V.} \frac{\pi}{n} \left( \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^j(\xi) - x_k^j(-1)) x'_k(\frac{2j\pi}{n})}{|x^j(-1) - x^j(\xi)|^2} A_{-1}(\xi) \frac{|x'(\frac{(2j+1+\xi)\pi}{n})|}{|x'(\frac{2j\pi}{n})|} d\xi \right. \\
& \left. + \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^{j-1}(\xi) - x_k^{j-1}(1)) x'_k(\frac{2j\pi}{n})}{|x^{j-1}(1) - x^{j-1}(\xi)|^2} A_1(\xi) \frac{|x'(\frac{(2j-1+\xi)\pi}{n})|}{|x'(\frac{2j\pi}{n})|} d\xi \right)
\end{aligned}$$

and if  $x = x((2j+1)\pi/n)$ , above integral becomes to

$$\begin{aligned}
& \sum_{i \neq j} \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{2j+1\pi}{n})) x'_k(\frac{2j+1\pi}{n})}{|x(\frac{2j+1\pi}{n}) - x^i(\xi)|^2} \phi(x^i(\xi)) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{2j+1\pi}{n})|} d\xi \\
& + \text{P.V.} \sum_{i=j, j-1} \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{2j+1\pi}{n})) x'_k(\frac{2j+1\pi}{n})}{|x(\frac{2j+1\pi}{n}) - x^i(\xi)|^2} \phi(x^i(\xi)) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{2j+1\pi}{n})|} d\xi \\
& \approx \sum_{i \neq j} \sum_{l=-1}^1 \phi(x^i(l)) \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{(2j+1)\pi}{n})) x'_k(\frac{(2j+1)\pi}{n})}{|x(\frac{(2j+1)\pi}{n}) - x^i(\xi)|^2} A_l(\xi) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{(2j+1)\pi}{n})|} d\xi \\
& + \phi(x(\frac{(2j+1)\pi}{n})) \text{P.V.} \frac{\pi}{n} \left( \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^j(\xi) - x_k^j(0)) x'_k(\frac{(2j+1)\pi}{n})}{|x^j(0) - x^j(\xi)|^2} A_0(\xi) \frac{|x'(\frac{((2j+1)+\xi)\pi}{n})|}{|x'(\frac{(2j+1)\pi}{n})|} d\xi \right)
\end{aligned}$$

where  $x^i(\xi) = x((2i+1+\xi)\pi/n)$ . For simplicity, we denote a 3-D tensor  $M_{jil}$ :

$$M_{jil} = \frac{\pi}{n} \int_{-1}^1 \frac{\sum_{k=1,2} (x_k^i(\xi) - x_k \frac{j\pi}{n})) x'_k(\frac{j\pi}{n})}{|x(\frac{j\pi}{n}) - x^i(\xi)|^2} A_l(\xi) \frac{|x'(\frac{(2i+1+\xi)\pi}{n})|}{|x'(\frac{j\pi}{n})|} d\xi$$

Then, the general Matrix is

$$G_{ji} = \begin{cases} M_{j,i,-1} + M_{j,i-1,1} & j \text{ is even} \\ M_{j,i,0} & j \text{ is odd} \end{cases}$$

## 10. Traction Tenson of Neumann Green Function

$$\hat{\Phi}(\xi, x_2; y_2) = \frac{\mathbf{i}}{2\omega^2} \left[ \begin{pmatrix} \mu_s & -\xi \frac{x_2-y_2}{|x_2-y_2|} \\ -\xi \frac{x_2-y_2}{|x_2-y_2|} & \frac{\xi^2}{\mu_s} \end{pmatrix} e^{\mathbf{i}\mu_s|x_2-y_2|} + \begin{pmatrix} \frac{\xi^2}{\mu_p} & \xi \frac{x_2-y_2}{|x_2-y_2|} \\ \xi \frac{x_2-y_2}{|x_2-y_2|} & \mu_p \end{pmatrix} e^{\mathbf{i}\mu_p|x_2-y_2|} \right]$$

$$\sigma(\Phi)(\xi, x_2; y_2) e_1 = \frac{\mu}{2\omega^2} \left[ \begin{pmatrix} -2\xi\mu_s & \frac{x_2-y_2}{|x_2-y_2|} 2\xi^2 \\ -\frac{x_2-y_2}{|x_2-y_2|} \beta & \frac{\xi\beta}{\mu_s} \end{pmatrix} e^{\mathbf{i}\mu_s|x_2-y_2|} + \begin{pmatrix} -\frac{\alpha\xi}{\mu_p} & -\frac{x_2-y_2}{|x_2-y_2|} \alpha \\ -\frac{x_2-y_2}{|x_2-y_2|} 2\xi^2 & -2\xi\mu_p \end{pmatrix} e^{\mathbf{i}\mu_p|x_2-y_2|} \right]$$



$$\sigma(\Phi)(\xi, x_2; y_2)e_2 = \frac{\mu}{2\omega^2} \left[ \begin{pmatrix} -\frac{x_2-y_2}{|x_2-y_2|}\beta & \frac{\xi\beta}{2\xi\mu_s} \\ 2\xi\mu_s & -\frac{x_2-y_2}{|x_2-y_2|}2\xi^2 \end{pmatrix} e^{\mathbf{i}\mu_s|x_2-y_2|} + \begin{pmatrix} -\frac{x_2-y_2}{|x_2-y_2|}2\xi^2 & -2\xi\mu_p \\ -\frac{\beta\xi}{\mu_p} & -\frac{x_2-y_2}{|x_2-y_2|}\beta \end{pmatrix} e^{\mathbf{i}\mu_p|x_2-y_2|} \right]$$

where  $\alpha(\xi) = k_s^2 - 2\mu_p^2$ ,  $\beta(\xi) = k_s^2 - 2\xi^2$ .

$$\hat{N}(\xi, x_2; y_2) = \hat{\Phi}(\xi, x_2; y_2) - \hat{\Phi}(\xi, x_2; -y_2) + \hat{N}_c(\xi, x_2; y_2) \quad (10.1)$$

$$\begin{aligned} \hat{N}_c(\xi, x_2; y_2) = \frac{\mathbf{i}}{\omega^2\delta(\xi)} & \left\{ A(\xi)e^{\mathbf{i}\mu_s(x_2+y_2)} + B(\xi)e^{\mathbf{i}\mu_p(x_2+y_2)} \right. \\ & \left. + C(\xi)e^{\mathbf{i}\mu_s x_2 + \mu_p y_2} + D(\xi)e^{\mathbf{i}\mu_p x_2 + \mu_s y_2} \right\} \end{aligned} \quad (10.2)$$

where

$$\begin{aligned} A(\xi) &= \begin{pmatrix} \mu_s\beta^2 & -4\xi^3\mu_s\mu_p \\ -\xi\beta^2 & 4\xi_4\mu_p \end{pmatrix} & B(\xi) &= \begin{pmatrix} 4\xi^4\mu_s & \xi\beta^2 \\ 4\xi^3\mu_s\mu_p & \mu_p\beta^2 \end{pmatrix} \\ C(\xi) &= \begin{pmatrix} 2\xi^2\mu_s\beta & -2\xi\mu_s\mu_p\beta \\ -2\xi^3\beta & 2\xi^2\mu_p\beta \end{pmatrix} & D(\xi) &= \begin{pmatrix} 2\xi^2\mu_s\beta & 2\xi^3\beta \\ 2\xi\mu_s\mu_p\beta & 2\xi^2\mu_p\beta \end{pmatrix} \end{aligned}$$

The traction of integral part  $N_c$ :

$$\begin{aligned} \sigma(N_c(\xi, x_2; y_2))e_1 &= \frac{-\mu}{\omega^2\delta(\xi)} \left\{ A(\xi)e^{\mathbf{i}\mu_s(x_2+y_2)} + B(\xi)e^{\mathbf{i}\mu_p(x_2+y_2)} \right. \\ & \left. + C(\xi)e^{\mathbf{i}\mu_s x_2 + \mu_p y_2} + D(\xi)e^{\mathbf{i}\mu_p x_2 + \mu_s y_2} \right\} \end{aligned}$$

where

$$\begin{aligned} A(\xi) &= \begin{pmatrix} 2\xi\mu_s\beta^2 & -8\mu_s\mu_p\xi^4 \\ \beta^3 & -4\xi^3\mu_p\beta \end{pmatrix} & B(\xi) &= \begin{pmatrix} 4\xi^3\mu_s\alpha & \alpha\beta^2 \\ 8\xi^4\mu_s\mu_p & 2\xi\mu_p\beta^2 \end{pmatrix} \\ C(\xi) &= \begin{pmatrix} 4\xi^3\mu_s\beta & -4\xi^2\mu_s\mu_p\beta \\ 2\xi^2\beta^2 & -2\xi\mu_p\beta^2 \end{pmatrix} & D(\xi) &= \begin{pmatrix} 2\xi\mu_s\alpha\beta & 2\xi^2\alpha\beta \\ 4\xi^2\mu_s\mu_p\beta & 4\xi^3\mu_p\beta \end{pmatrix} \end{aligned}$$

In particular, for  $y_2 = 0$ , a more simpler form are deduced:

$$\sigma(N(\xi, x_2; y_2))e_1 = \frac{-1}{\delta(\xi)} \left\{ \begin{pmatrix} 2\xi\mu_s\beta & -4\mu_s\mu_p\xi^2 \\ \beta^2 & -2\xi\mu_p\beta \end{pmatrix} e^{\mathbf{i}\mu_s x_2} + \begin{pmatrix} 2\xi\mu_s\alpha & \alpha\beta \\ 4\xi^2\mu_s\mu_p & 2\xi\mu_p\beta \end{pmatrix} e^{\mathbf{i}\mu_p x_2} \right\}$$

and

$$\begin{aligned} \sigma(N_c(\xi, x_2; y_2))e_2 &= \frac{-\mu}{\omega^2\delta(\xi)} \left\{ A(\xi)e^{\mathbf{i}\mu_s(x_2+y_2)} + B(\xi)e^{\mathbf{i}\mu_p(x_2+y_2)} \right. \\ & \left. + C(\xi)e^{\mathbf{i}\mu_s x_2 + \mu_p y_2} + D(\xi)e^{\mathbf{i}\mu_p x_2 + \mu_s y_2} \right\} \end{aligned}$$

where

$$\begin{aligned} A(\xi) &= \begin{pmatrix} \beta^3 & -4\xi^3\mu_p\beta \\ -2\xi\mu_s\beta^2 & 8\mu_s\mu_p\xi^4 \end{pmatrix} & B(\xi) &= \begin{pmatrix} 8\xi^4\mu_s\mu_p & 2\xi\mu_p\beta^2 \\ 4\xi^3\mu_s\beta & \beta^3 \end{pmatrix} \\ C(\xi) &= \begin{pmatrix} 2\xi^2\beta^2 & -2\xi\mu_p\beta^2 \\ -4\xi^3\mu_s\beta & 4\xi^2\mu_s\mu_p\beta \end{pmatrix} & D(\xi) &= \begin{pmatrix} 4\xi^2\mu_s\mu_p\beta & 4\xi^3\mu_p\beta \\ 2\xi\mu_s\beta^2 & 2\xi^2\beta^2 \end{pmatrix} \end{aligned}$$

Similarly, for  $y_2 = 0$ , a more simpler form are deduced:

$$\sigma(N(\xi, x_2; y_2))e_2 = \frac{-1}{\delta(\xi)} \left\{ \begin{pmatrix} \beta^2 & -2\xi\mu_p\beta \\ -2\xi\mu_s\beta & 4\mu_s\mu_p\xi^2 \end{pmatrix} e^{\mathbf{i}\mu_s x_2} + \begin{pmatrix} 4\xi^2\mu_s\mu_p & 2\xi\mu_p\beta \\ 2\xi\mu_s\beta & \beta^2 \end{pmatrix} e^{\mathbf{i}\mu_p x_2} \right\}$$

where  $\delta(\xi) = \beta^2 + 4\xi^2\mu_s\mu_p$

## 11. reflection of Plane wave

### 11.1. P-wave

We denote incident P-wave [1, p172] as

$$u^0 = A_0(\sin t_0, \cos t_0)^T e^{\mathbf{i}k_p(x_1 \sin t_0 + x_2 \cos t_0)} \quad (11.1)$$

and its stress as

$$\sigma(u^0) = \mathbf{i}k_p A_0(2\mu \sin t_0 \cos t_0, \lambda + 2\mu \cos^2 t_0)^T e^{\mathbf{i}k_p(x_1 \sin t_0 + x_2 \cos t_0)}$$

The reflected P-wave is represented as

$$\begin{aligned} u^1 &= A_1(\sin t_1, -\cos t_1)^T e^{\mathbf{i}k_p(x_1 \sin t_1 - x_2 \cos t_1)} \\ \sigma(u^1) &= \mathbf{i}k_p A_1(-2\mu \sin t_1 \cos t_1, \lambda + 2\mu \cos^2 t_1)^T e^{\mathbf{i}k_p(x_1 \sin t_1 + x_2 \cos t_1)} \end{aligned}$$

and reflected S-wave as

$$\begin{aligned} u^2 &= A_2(\cos t_2, \sin t_2)^T e^{\mathbf{i}k_s(x_1 \sin t_2 - x_2 \cos t_2)} \\ \sigma(u^2) &= \mathbf{i}k_s A_2(\mu(\sin^2 t_2 - \cos^2 t_2), -2\mu \sin t_2 \cos t_2)^T e^{\mathbf{i}k_s(x_1 \sin t_2 - x_2 \cos t_2)} \end{aligned}$$

We consider the clamped condition, then the total field on the  $x_2 = 0$  vanish:

$$u^0(x_1, 0) + u^1(x_1, 0) + u^2(x_1, 0) = 0$$

for any  $x_1 \in \mathbb{R}$ . A simple computation show that

$$\begin{aligned} t_1 = t_0 \quad \text{and} \quad \frac{\sin t_2}{\sin t_0} &= \frac{k_p}{k_s} := \kappa \\ A_0 = \cos(t_0 - t_2) \quad A_1 &= \cos(t_0 + t_2) \quad A_2 = -\sin 2t_0 \end{aligned}$$

### 11.2. S-wave

Similarly, we denote incident S-wave as

$$u^0 = A_0(-\cos t_0, \sin t_0)^T e^{\mathbf{i}k_p(x_1 \sin t_0 + x_2 \cos t_0)} \quad (11.2)$$

$$\sigma(u^0) = \mathbf{i}k_s(\mu(\sin^2 t_0 - \cos^2 t_0), 2\mu \sin t_0 \cos t_0)^T e^{\mathbf{i}k_p(x_1 \sin t_0 + x_2 \cos t_0)} \quad (11.3)$$

The reflected P-wave is represented as

$$\begin{aligned} u^1 &= A_1(\sin t_1, -\cos t_1)^T e^{\mathbf{i}k_p(x_1 \sin t_1 - x_2 \cos t_1)} \\ \sigma(u^1) &= \mathbf{i}k_p A_1(-2\mu \sin t_1 \cos t_1, \lambda + 2\mu \cos^2 t_1)^T e^{\mathbf{i}k_p(x_1 \sin t_1 + x_2 \cos t_1)} \end{aligned}$$

and reflected S-wave as

$$\begin{aligned} u^2 &= A_2(\cos t_2, \sin t_2)^T e^{\mathbf{i}k_s(x_1 \sin t_2 - x_2 \cos t_2)} \\ \sigma(u^2) &= \mathbf{i}k_s A_2(\mu(\sin^2 t_2 - \cos^2 t_2), -2\mu \sin t_2 \cos t_2)^T e^{\mathbf{i}k_s(x_1 \sin t_2 - x_2 \cos t_2)} \end{aligned}$$

The result is

$$\begin{aligned} t_2 = t_0 \quad \text{and} \quad \frac{\sin t_1}{\sin t_0} &= \frac{k_s}{k_p} = \frac{1}{\kappa} \\ A_0 &= \cos(t_0 - t_1) \quad A_1 = \sin 2t_0 \quad A_2 = \cos(t_0 + t_1) \end{aligned}$$

## 12. scattering relation of elastic wave

The solution for the scattering of a plane P-wave  $u_p$  (or S-wave  $u_s$ ) with incident direction  $d_0$  at a plane  $\Gamma := x \in \mathbb{R}^2 : x \cdot \nu = 0$  through the origin with normal vector  $\nu$  is described by

$$u = u_p + u_{p,p} + u_{p,s} = A_0 d_0 e^{\mathbf{i}k_p x \cdot d} + A_1 d_1 e^{\mathbf{i}k_p x \cdot d_1} + A_2 d_2^\perp e^{\mathbf{i}k_s x \cdot d_2} \quad (12.1)$$

$$u = u_s + u_{s,p} + u_{s,s} = A_0 d_0^\perp e^{\mathbf{i}k_s x \cdot d} + A_1 d_1 e^{\mathbf{i}k_p x \cdot d_1} + A_2 d_2^\perp e^{\mathbf{i}k_s x \cdot d_2} \quad (12.2)$$

where  $d_i = (d_i^1, d_i^2)^T$  are unit vectors,  $d_i^\perp = (d_i^2, -d_i^1)^T$  and  $A_i$  are corresponding amplitude. For fixed boundary, we have  $u = 0$  for  $x \in \Gamma$ . After a standard computation, we get for P-wave:

$$d_1 = d_0 - 2\alpha\nu \quad (12.3)$$

$$d_2 = \kappa d_0 - \beta\nu \quad (12.4)$$

$$A_0 = \kappa(d, \nu)^2 - \kappa(d, \nu^\perp)^2 - \beta(d, \nu) \quad (12.5)$$

$$A_1 = \kappa - \beta(d, \nu) \quad (12.6)$$

$$A_2 = -2(d, \nu)(d, \nu^\perp) \quad (12.7)$$

where  $\alpha = (d, \nu)$ ,  $\beta = \kappa\alpha - \sqrt{\kappa^2\alpha^2 - \kappa^2 + 1}$  and  $\kappa = k_p/k_s$ . For S-wave:

$$d_1 = \kappa_1 d_0 - \gamma\nu \quad (12.8)$$

$$d_2 = d_0 - 2\alpha\nu \quad (12.9)$$

$$A_0 = \kappa_1(d, \nu)^2 - \kappa_1(d, \nu^\perp)^2 - \gamma(d, \nu) \quad (12.10)$$

$$A_1 = 2(d, \nu)(d, \nu^\perp) \quad (12.11)$$

$$A_2 = \kappa_1 - \gamma(d, \nu) \quad (12.12)$$

where  $\gamma = \kappa_1\alpha - \sqrt{\kappa_1^2\alpha^2 - \kappa_1^2 + 1}$  and  $\kappa_1 = 1/\kappa$ . Thus the traction of  $u(x)$  on the plane  $\Gamma$  can be obtained. For P-wave

$$\begin{aligned} \sigma(u) \cdot \nu &= [\mathbf{i}k_p A_0(\lambda\nu + 2\mu(d_0, \nu)d_0) + \mathbf{i}k_p A_1(\lambda\nu + 2\mu(d_1, \nu)d_1) \\ &+ \mathbf{i}k_s A_2\mu((d_2, \nu)d_2^\perp + (d_2^\perp, \nu)d_2)]e^{\mathbf{i}k_p x \cdot d} := \mathbf{i}k_p Rf_p(x, d, \nu)e^{\mathbf{i}k_p x \cdot d} \end{aligned}$$

For S-wave

$$\begin{aligned} \sigma(u) \cdot \nu &= [\mathbf{i}k_s A_0\mu((d_0, \nu)d_0^\perp + (d_0^\perp, \nu)d_0) + \mathbf{i}k_p A_1(\lambda\nu + 2\mu(d_1, \nu)d_1) \\ &+ \mathbf{i}k_s A_2\mu((d_2, \nu)d_2^\perp + (d_2^\perp, \nu)d_2)]e^{\mathbf{i}k_s x \cdot d} := \mathbf{i}k_s Rf_s(x, d, \nu)e^{\mathbf{i}k_s x \cdot d} \end{aligned}$$

**Definition 12.1** For any unit vector  $d \in \mathbb{R}^2$ , let  $u_p^i = d e^{\mathbf{i}k_p x \cdot d}$  or  $u_s^i = d^\perp e^{\mathbf{i}k_s x \cdot d}$  be the incident wave and  $u_\alpha^s = u_\alpha^s(x; d)$  be the radiation solution of the Navier equation:

$$u_\alpha^s + \omega^2 u_\alpha^s = 0 \quad \text{in } \mathbb{R}^2 \setminus \bar{D} \quad (12.13)$$

$$u_\alpha^s = -u_\alpha^i \quad \text{on } \partial D \quad (12.14)$$

The scattering coecient  $R(x;d)$  for  $x \in \partial D$  is defined by the relation

$$\sigma(u_\alpha^s + u_\alpha^i) \cdot \nu = \mathbf{i}k_\alpha R_\alpha(x;d)e^{\mathbf{i}k_\alpha x \cdot d} \quad \text{on } \partial D$$

where  $\alpha = p, s$ .

In the case of high frequency approximation, the scattering coecient can be approximated by

$$R_\alpha(x;d) = \begin{cases} Rf_\alpha(x;d,\nu) & \text{if } x \in \partial D_d^- = \{x \in \partial D, \nu(x) \cdot d < 0\}, \\ 0 & \text{if } x \in \partial D_d^+ = \{x \in \partial D, \nu(x) \cdot d \geq 0\}. \end{cases}$$

### 13. Difference of solution of navier equation in full-space and half-space,0105

For any  $0 < \varepsilon < 1$ , we consider the problem

$$\Delta_\varepsilon u_1^\varepsilon + (1 + \mathbf{i}\varepsilon)\omega^2 u_1^\varepsilon = 0 \quad \text{in } \mathbb{R}_+^2 \setminus \bar{D} \quad (13.1)$$

$$u_1^\varepsilon = g \quad \text{on } \Gamma_D \quad (13.2)$$

$$\sigma(u_1^\varepsilon)e_2 = 0 \quad \text{on } \Gamma_0 \quad (13.3)$$

and

$$\Delta_\varepsilon u_2^\varepsilon + (1 + \mathbf{i}\varepsilon)\omega^2 u_2^\varepsilon = 0 \quad \text{in } \mathbb{R}^2 \setminus \bar{D} \quad (13.4)$$

$$u_2^\varepsilon = g \quad \text{on } \Gamma_D \quad (13.5)$$

Let  $w^\varepsilon(x)$  be the solution of the problem:

$$\Delta_\varepsilon w^\varepsilon + (1 + \mathbf{i}\varepsilon)\omega^2 w^\varepsilon = 0 \quad \text{in } \mathbb{R}_+^2 \quad (13.6)$$

$$\sigma(w^\varepsilon)e_2 = -\sigma(u_2^\varepsilon)e_2 \quad \text{on } \Gamma_0 \quad (13.7)$$

Then  $u_1^\varepsilon - u_2^\varepsilon - w^\varepsilon$  satisfies (13.1),(13.3) with the boundary condition  $u_1^\varepsilon - u_2^\varepsilon - w^\varepsilon = -w^\varepsilon$  on  $\Gamma_D$ . Thus by the limiting absorption principle, we have

$$\|T_x^\nu(u_1^\varepsilon - u_2^\varepsilon)\|_{H^{-1/2}(\Gamma_D)} \leq C(\|w^\varepsilon\|_{H^{1/2}(\Gamma_D)} + |T_x^\nu(w^\varepsilon)|_{H^{-1/2}(\Gamma_D)}) \quad (13.8)$$

$$\leq C \max_{x \in D} (|w^\varepsilon(x)| + d_D |\nabla w^\varepsilon(x)|) \quad (13.9)$$

where C is independent of  $\varepsilon, \omega$ . By the integral representation formula we have for any  $z \in \Gamma_0$

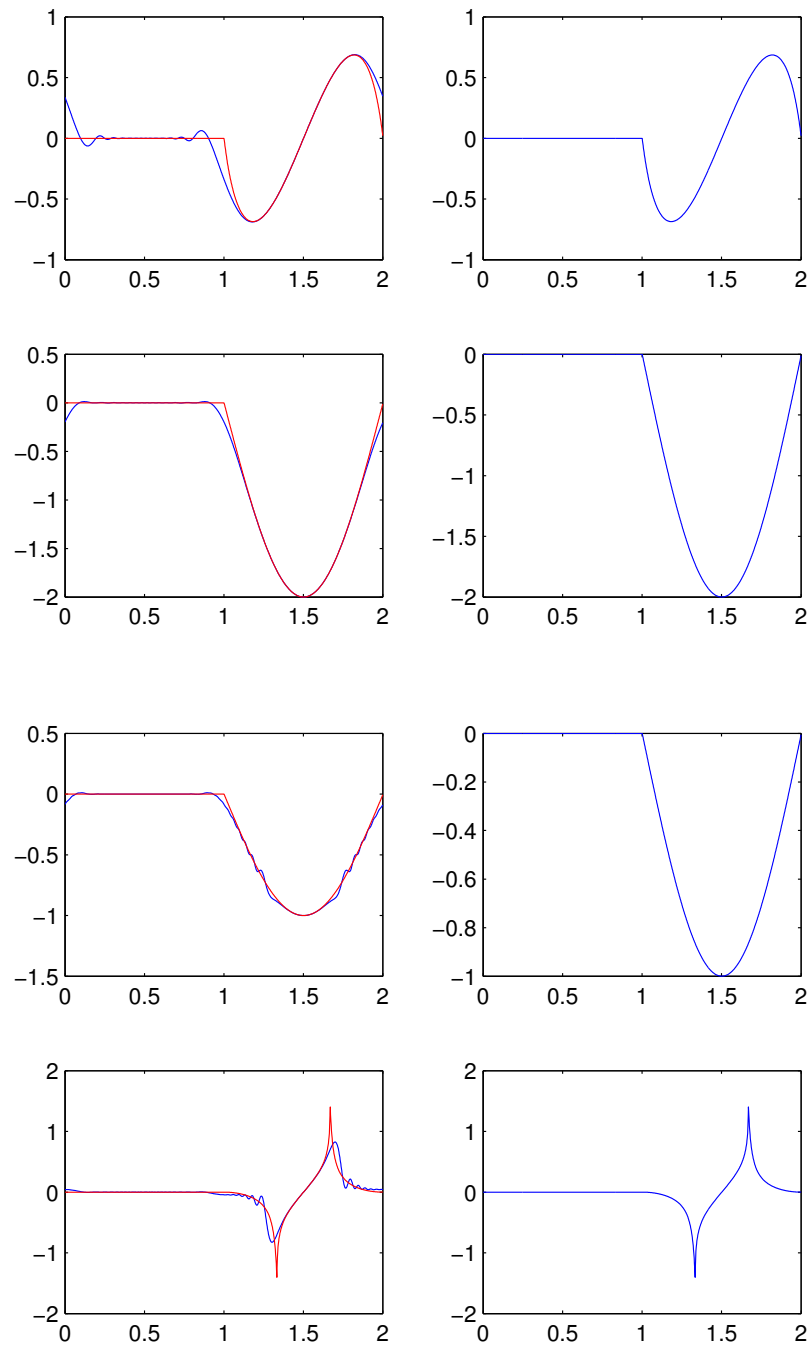
$$u_2^\varepsilon(z) = \int_{\Gamma_D} (T_y^\nu \Phi^\varepsilon(y, z))^T u_2^\varepsilon(y) - \Phi^\varepsilon(z, y) (T_y^\nu u_2^\varepsilon(y)) ds(y) \quad (13.10)$$

which yields by using the integral representation again that for  $x \in D$

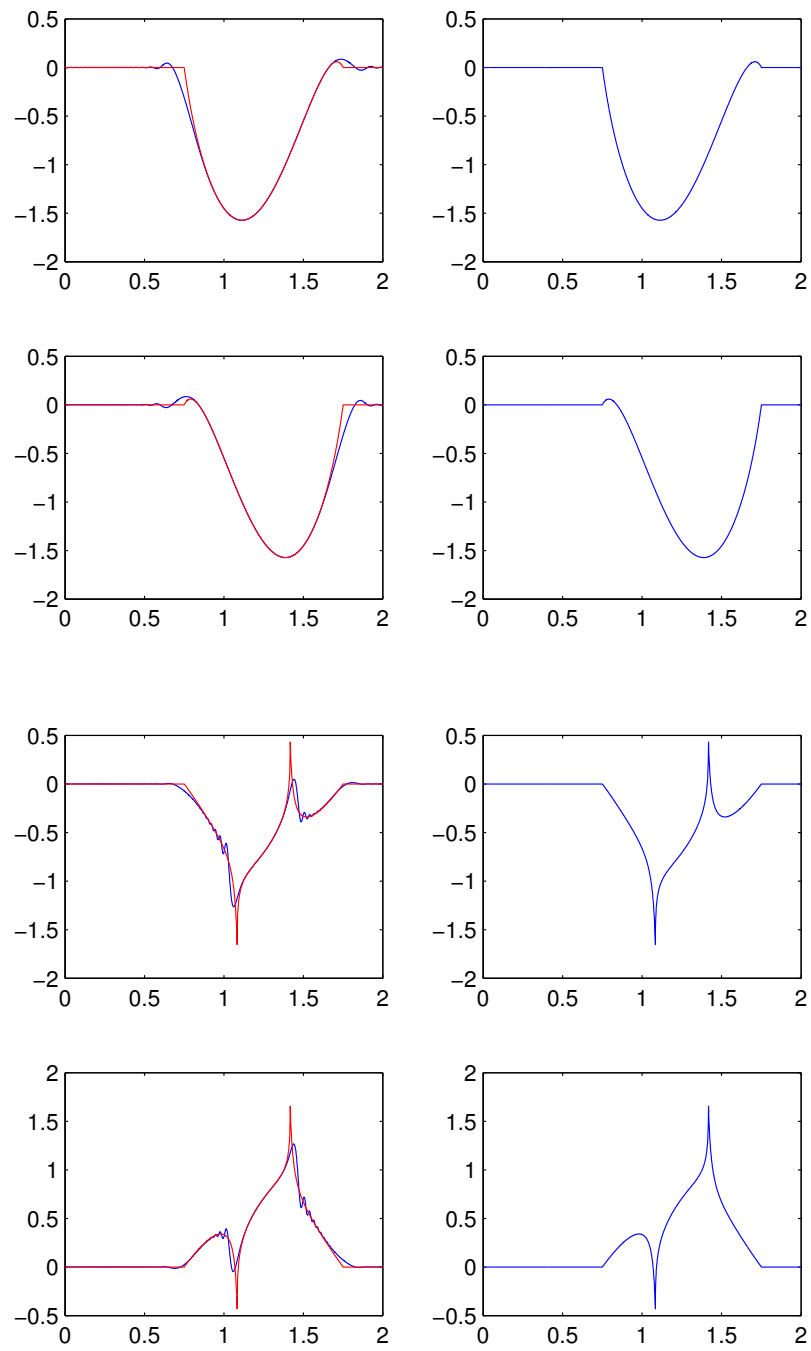
$$w^\varepsilon(x) = \int_{\Gamma_0} N^\varepsilon(x, z) (T_z^{e_2} u_2^\varepsilon(z)) ds(z) \quad (13.11)$$

$$= \int_{\Gamma_D} ds(y) \int_{\Gamma_0} N^\varepsilon(x, z) (T_z^{e_2} ((T_y^\nu \Phi^\varepsilon(y, z))^T)) ds(z) \quad (13.12)$$

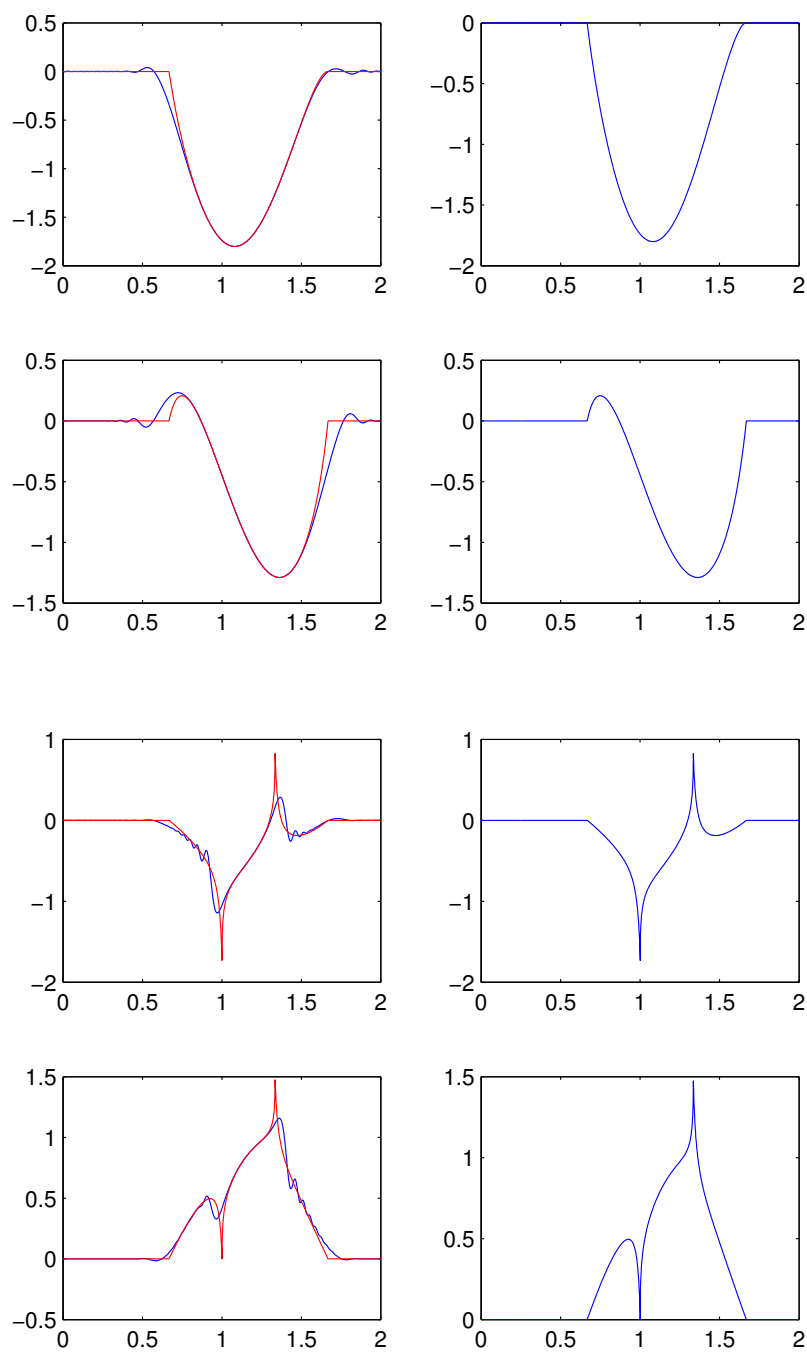
$$- \int_{\Gamma_D} v^\varepsilon(x, y) (T_y^\nu u_2^\varepsilon(y)) ds(y) \quad (13.13)$$



**Figure 1.**  $\theta = 0\pi$



**Figure 2.**  $\theta = \pi/4$



**Figure 3.**  $\theta = \pi/3$

$$= \int_{\Gamma_D} ds(y) \int_{\Gamma_0} N^\varepsilon(x, z) (T_z^{e2}(\Phi^\varepsilon(y, z))^T (T_y^\nu)^T) ds(z) \quad (13.14)$$

$$- \int_{\Gamma_D} v^\varepsilon(x, y) (T_y^\nu u_2^\varepsilon(y)) ds(y) \quad (13.15)$$

$$= \int_{\Gamma_D} ds(y) \int_{\Gamma_0} N^\varepsilon(x, z) (T_y^\nu (T_z^{e2} \Phi^\varepsilon(z, y))^T)^T ds(z) \quad (13.16)$$

$$- \int_{\Gamma_D} v^\varepsilon(x, y) (T_y^\nu u_2^\varepsilon(y)) ds(y) \quad (13.17)$$

$$= \int_{\Gamma_D} (T_y^\nu (v^\varepsilon(x, y))^T)^T u_2^\varepsilon(y) - v^\varepsilon(x, y) (T_y^\nu u_2^\varepsilon(y)) ds(y) \quad (13.18)$$

where

$$v^\varepsilon(x, y) = \int_{\Gamma_0} N^\varepsilon(x, z) (T_z^{e2} \Phi^\varepsilon(z, y)) ds(z) \quad (13.19)$$

Since  $\|T_x^\nu(u_2^\varepsilon)\|_{H^{-1/2}(\Gamma_D)} \leq C\|g\|_{H^{1/2}(\Gamma_D)}$ , we obtain

$$|w^\varepsilon(x)| \leq C\|g\|_{H^{1/2}(\Gamma_D)} \max_{x \in D} (|v^\varepsilon(x, y)| + d_D |\nabla_y v^\varepsilon(x, y)|) \quad (13.20)$$

and

$$|\nabla w^\varepsilon(x)| \leq C\|g\|_{H^{1/2}(\Gamma_D)} \max_{x \in D} (|\nabla_x v^\varepsilon(x, y)| + d_D |\nabla_x \nabla_y v^\varepsilon(x, y)|) \quad (13.21)$$

By (13.8) and letting  $\varepsilon \rightarrow 0^+$ , we have

$$\|T_x^\nu(u_1 - u_2)\|_{H^{-1/2}(\Gamma_D)} \leq C\|g\|_{H^{1/2}(\Gamma_D)} \max_{x \in D} \lim_{\varepsilon \rightarrow 0^+} (|v^\varepsilon(x, y)| \quad (13.22)$$

$$+ d_D |\nabla_y v^\varepsilon(x, y)| + d_D |\nabla_x v^\varepsilon(x, y)| + d_D^2 |\nabla_x \nabla_y v^\varepsilon(x, y)|) \quad (13.23)$$

where  $u_1$  is the scattering solution in the half-space and  $u_2$  in the full-space. Now, it turns to estimate  $v^\varepsilon(x, y)$ . Applying the Fourier transformation to the first horizontal variable of  $N^\varepsilon(z, x)$  and  $T_z^{e2} \Phi^\varepsilon(z, y)$ , we have

$$\mathcal{F}[N^\varepsilon](\xi, 0; x) = \frac{\mathbf{i}}{\mu \delta(\xi)} \left[ \begin{pmatrix} 2\xi^2 \mu_s & -2\xi \mu_s \mu_p \\ -\xi \beta & \mu_p \beta \end{pmatrix} e^{\mathbf{i} \mu_p x_2} + \begin{pmatrix} \mu_s \beta & \xi \beta \\ 2\xi \mu_s \mu_p & 2\xi^2 \mu_p \end{pmatrix} e^{\mathbf{i} \mu_s x_2} \right] e^{-\mathbf{i} \xi x_1}$$

$$\mathcal{F}[T_z^{e2} \Phi^\varepsilon](\xi, 0; y) = \frac{\mu}{2\omega^2} \left[ \begin{pmatrix} 2\xi^2 & -2\xi \mu_p \\ -\frac{\beta \xi}{\mu_p} & \beta \end{pmatrix} e^{\mathbf{i} \mu_p y_2} + \begin{pmatrix} \beta & \frac{\xi \beta}{\mu_s} \\ 2\xi \mu_s & 2\xi^2 \end{pmatrix} e^{\mathbf{i} \mu_s y_2} \right] e^{-\mathbf{i} \xi y_1}$$

Using Parseval identity combined with above two formula, we have

$$\lim_{\varepsilon \rightarrow 0^+} v^\varepsilon(x, y) = \lim_{\varepsilon \rightarrow 0^+} \int_{\mathbb{R}} \mathcal{F}[N^\varepsilon](\xi, 0; x)^T \mathcal{F}[T_z^{e2} \Phi^\varepsilon](-\xi, 0; y) d\xi$$

**Lemma 13.1** *For any  $x, y \in D$ , let*

$$p(x, y) = \lim_{\varepsilon \rightarrow 0^+} p^\varepsilon(x, y) := \lim_{\varepsilon \rightarrow 0^+} \int_{\mathbb{R}} \frac{f(\mu_p^\varepsilon, \mu_s^\varepsilon, \xi)}{\delta^\varepsilon(\xi)} e^{\mathbf{i} \mu_\alpha^\varepsilon x_2 + \mathbf{i} \mu_\beta^\varepsilon y_2 + \mathbf{i} \xi (y_1 - x_1)} d\xi$$

where  $f(a, b, c)$  is a homogeneous fifth order polynomial with respect to  $a, b, c$  and  $\alpha = s, p$ ,  $\beta = s, p$ . Then there exists a constant  $C > 0$  only dependent on  $\kappa$  such that

$$|p(x, y)| + k_s^{-1} |\nabla_x p(x, y)| + k_s^{-1} |\nabla_y p(x, y)| + k_s^{-2} |\nabla_x \nabla_y p(x, y)| \leq C((k_s h)^{-1/2} + e^{-\sqrt{k_R^2 - k_s^2} h})$$

uniformly for  $x, y \in D$ .



**Proof.** Without loss of generality, we assume  $k_\alpha \leq k_\beta$ . Then we can divide  $p(x, y)$  into two parts:

$$\begin{aligned} p(x, y) &= \lim_{\varepsilon \rightarrow 0^+} \int_{I_1} + \int_{I_2} \frac{f(\mu_p^\varepsilon, \mu_s^\varepsilon, \xi)}{(k_\alpha^\varepsilon)^2 \delta^\varepsilon(\xi)} e^{i\mu_\alpha^\varepsilon x_2 + i\mu_\beta^\varepsilon y_2 + i\xi(y_1 - x_1)} d\xi \\ &= \int_{I_1} \frac{f(\mu_p, \mu_s, \xi)}{k_\alpha^2 \delta(\xi)} e^{i\mu_\alpha x_2 + i\mu_\beta y_2 + i\xi(y_1 - x_1)} d\xi \\ &\quad + \lim_{\varepsilon \rightarrow 0^+} \int_{I_2} \frac{f(\mu_p^\varepsilon, \mu_s^\varepsilon, \xi)}{(k_\alpha^\varepsilon)^2 \delta^\varepsilon(\xi)} e^{i\mu_\alpha^\varepsilon x_2 + i\mu_\beta^\varepsilon y_2 + i\xi(y_1 - x_1)} d\xi \\ &= p_1(x, y) + p_2(x, y) \end{aligned}$$

where  $I_1 = (-k_\alpha, k_\alpha)$ ,  $I_2 = (-2k_R + k_\alpha, k_\alpha) \cup (k_\alpha, 2k_R - k_\alpha)$  and  $I_2 = R \setminus [-k_\alpha, k_\alpha]$ . Substituting  $\xi = k_\alpha t$  into  $p_1(x, y)$ , we get

$$p_1(x, y) = \int_{-1}^1 \frac{f(\mu_p(k_\alpha t), \mu_s(k_\alpha t), k_\alpha t)}{k_\alpha \delta(k_\alpha t)} e^{ik_\alpha x_2(\sqrt{1-t^2} + \tau\sqrt{\varsigma^2-t^2} + \gamma t)} dt$$

where  $\tau = y_2/x_2$ ,  $\varsigma = k_\beta/k_\alpha$  and  $\gamma = (y_1 - x_1)/x_2$ . It is easy to see that the phase function  $\phi(t) = \sqrt{1-t^2} + \tau\sqrt{\varsigma^2-t^2} + \gamma t$  satisfies  $|\phi''(t)| \geq 1/(1-t^2)^{3/2} \geq 1$  for  $t \in (-1, 1)$ . Then we can obtain  $|p_1(x, y)| \leq C1/(k_s h)^{1/2}$  by lemma 6.1.

For  $p_2(x, y)$ , by changing the integration path and using same argument as in the proof of estimate for  $\text{psf}$ , we can easily obtain:

$$|p_2(x, y)| \leq C\left(\frac{1}{k_s h} + e^{-\sqrt{k_R^2 - k_s^2} h}\right)$$

This completes the proof of the estimate for  $|p(x, y)|$ . The other estimates can be proved by a similar argument. We omit the details  $\square$

**Lemma 13.2** For any  $x, y \in D$ , let

$$p(x, y) = \lim_{\varepsilon \rightarrow 0^+} p^\varepsilon(x, y) := \lim_{\varepsilon \rightarrow 0^+} \int_{\mathbb{R}} \frac{f(\mu_p^\varepsilon, \mu_s^\varepsilon, \xi)}{\delta^\varepsilon(\xi)} e^{i\mu_\alpha^\varepsilon x_2 + i\mu_\beta^\varepsilon y_2 + i\xi(y_1 - x_1)} d\xi$$

where  $f(a, b, c)$  is a homogeneous fifth order polynomial with respect to  $a, b, c$  and  $\alpha = s, p$ ,  $\beta = s, p$ . Then there exists a constant  $C > 0$  only dependent on  $\kappa$  such that

$$|p(x, y)| + k_s^{-1} |\nabla_x p(x, y)| + k_s^{-1} |\nabla_y p(x, y)| + k_s^{-2} |\nabla_x \nabla_y p(x, y)| \leq C(1 + k_s d_D)((k_s h)^{-1/2} + e^{-\sqrt{k_R^2 - k_s^2} h})$$

uniformly for  $x, y \in D$ .

**Proof.** Without loss of generality, we assume  $k_\alpha \leq k_\beta$ . Then we can divide  $p(x, y)$  into four parts:

$$\begin{aligned} p(x, y) &= \lim_{\varepsilon \rightarrow 0^+} \int_{I_1} + \int_{I_2} + \int_{I_3} \frac{f(\mu_p^\varepsilon, \mu_s^\varepsilon, \xi)}{(k_\alpha^\varepsilon)^2 \delta^\varepsilon(\xi)} e^{i\mu_\alpha^\varepsilon x_2 + i\mu_\beta^\varepsilon y_2 + i\xi(y_1 - x_1)} d\xi \\ &= \int_{I_1} + \text{PV} \int_{I_2} + \int_{I_3} \frac{f(\mu_p, \mu_s, \xi)}{k_\alpha^2 \delta(\xi)} e^{i\mu_\alpha x_2 + i\mu_\beta y_2 + i\xi(y_1 - x_1)} d\xi \\ &\quad + i\pi \left( \frac{f(\mu_p(k_R), \mu_s(k_R), k_R)}{k_\alpha^2 \delta'(k_R)} e^{i\mu_\alpha(k_R)x_2 + i\mu_\beta(k_R)y_2 + ik_R(y_1 - x_1)} \right) \end{aligned}$$

$$\begin{aligned}
& - \frac{f(\mu_p(k_R), \mu_s(k_R), -k_R)}{k_\alpha^2 \delta'(-k_R)} e^{\mathbf{i}\mu_\alpha(k_R)x_2 + \mathbf{i}\mu_\beta(k_R)y_2 - \mathbf{i}k_R(y_1 - x_1)} \\
& : \quad = p_1(x, y) + p_2(x, y) + p_3(x, y) + p_4(x, y)
\end{aligned}$$

where  $I_1 = (-k_\alpha, k_\alpha)$ ,  $I_2 = (-2k_R + k_\alpha, k_\alpha) \cup (k_\alpha, 2k_R - k_\alpha)$  and  $I_2 = R \setminus [-2k_R + k_\alpha, 2k_R - k_\alpha]$ . Substituting  $\xi = k_\alpha t$  into  $p_1(x, y)$ , we get

$$p_1(x, y) = \int_{-1}^1 \frac{f(\mu_p(k_\alpha t), \mu_s(k_\alpha t), k_\alpha t)}{k_\alpha \delta(k_\alpha t)} e^{\mathbf{i}k_\alpha x_2(\sqrt{1-t^2} + \tau\sqrt{\varsigma^2-t^2} + \gamma t)} dt$$

where  $\tau = y_2/x_2$ ,  $\varsigma = k_\beta/k_\alpha$  and  $\gamma = (y_1 - x_1)/x_2$ . It is easy to see that the phase function  $\phi(t) = \sqrt{1-t^2} + \tau\sqrt{\varsigma^2-t^2} + \gamma t$  satisfies  $|\phi''(t)| \geq 1/(1-t^2)^{3/2} \geq 1$  for  $t \in (-1, 1)$ . Then we can obtain  $|p_1(x, y)| \leq C1/(k_s h)^{1/2}$  by lemma 6.1.

Let

$$g_\pm(\xi) = \frac{f(\mu_p, \mu_s, \xi)(\xi \pm k_R)}{\delta(\xi)} e^{\mathbf{i}\mu_\alpha x_2 + \mathbf{i}\mu_\beta y_2 + \mathbf{i}\xi(y_1 - x_1)} d\xi$$

Then by the definition of cauchy principle value, we have

$$p_2(x, y) = \int_{-2k_R+k_\alpha}^{-k_\alpha} \frac{g_-(\xi) - g_-(-k_R)}{x + k_R} d\xi + \int_{k_\alpha}^{2k_R-k_\alpha} \frac{g_+(\xi) - g_+(k_R)}{x - k_R} d\xi$$

□

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