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Generalizations of 2D-Canonical Sine-Sine Transform

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GENERALIZATIONS OF 2D-CANONICAL SINE-SINE TRANSFORM

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Ref.

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Generalizations of 2D-Canonical Sine-Sine Transform

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I. Introduction

Integral transforms have been successfully used for almost two centuries is solving many problems in mathematical physical, applied mathematics and engineering science. Historically origin of the integral transform is P.S. Laplace and J.Fourier. Laplace transform is useful, for evaluating certain definite integral [2].

The definition of canonical sine-sine transform as follows [1].

$$\{2DCSST\, f(t,x)\}(s,w) = \langle f(t,x), K_{s_1}(t,x) K_{s_2}(x,w) \rangle$$

In the present paper, 2D sine-sine transform is extended in the distribution sense. The plan of the paper is as follows. The definitions are given in section 2. In section 3, testing functionspace is defined by Galfand-shilovtechnique [3],[4].Section 4 some result on countable union space are proved. In section5, inversion and uniqueness theorem are stated. In section 6, modulations theorems are given. The notations and terminology as per zemanian [5],[6].

II. Definition Two Dimensional Canonical Sine-Sine Transform

Let $E'(R\times R)$ denote the dual of $E(R\times R)$. Therefore the generalized canonical sine transform of $f(t,x)\in E'(R\times R)$ is defined as

$$\{2DCST\, f(t,x)\}(s,w)$$

$$=(-1)\frac{1}{\sqrt{2\pi ib}}\frac{1}{\sqrt{2\pi ib}} e^{\frac{i}{2}\left(\frac{d}{b}\right)s^2} e^{\frac{i}{2}\left(\frac{d}{b}\right)w^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right) e^{\frac{i}{2}\left(\frac{a}{b}\right)t^2} e^{\frac{i}{2}\left(\frac{a}{b}\right)x^2} f(t,x)\,dxdt$$

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Where $$\gamma_{E,k}\left\{K_{s_1}(t,s)K_{s_2}(x,w)\right\} = \sup_{\substack{-\infty<t<\infty\\ -\infty<x<\infty}}\left|D_t^k D_x^l K_{s_1}(t,s)K_{s_2}(x,w)\right| < \infty$$

III. Different S-Type Testing Function Spaces

In this section we have defined s-type testing function spaces by imposing conditions not only on the decreases of the fundamental functions at infinity, but also on the growth of their derivatives as the order of derivative increases. Clearly, $SS^{a,b}$ space will be extension of testing function space D, so that these spaces have been successfully, used in pseudo differential operator theory.

a) The space $SS_\gamma^{a,b}$:

It is given by

$$SS_\gamma^{a,b} = \left\{\phi : \phi \in E_+ \,/\, \sigma_{l,k,p}\phi(t,x) = \sup_{I_1}\left|t^l D_t^k D_x^p \phi(t,x)\right| \le C_{kp} A^l . l^{l\gamma}\right\} \tag{3.1}$$

The constant $C_{k,p}$ and A depend on ϕ.

b) The space $SS^{ab,\beta}$:

$SS^{a,b,\beta}$ this space is given by

$$SS^{a,b,\beta} = \left\{\phi.\phi \in E_+ \,/\, \rho_{l,k,p}\phi(t,x) = \sup\left|t^l D_t^k D_x^p \phi(t,x)\right| \le C_{l,p} B^k k^{k\beta}\right\} \tag{3.2}$$

The constants $C_{l,p}$ and B depend on ϕ.

c) The space $SS_\gamma^{a,b,\beta}$

This space is formed by combining the condition (3.1) and (3.2)

$$SS_\gamma^{a,b,\beta} = \left\{\phi : \phi \in E_+ \,/\, \xi_{l,k,p}\phi(t,x) = \sup_{I_1}\left|t^l D_t^k D_x^p \phi(t,x)\right| \le C\, A^l l^{l\gamma} B^k k^{k,\beta}\right\} \tag{3.3}$$

$l,k,p = 0,1,2$........... Where A,B,C depend on ϕ.

d) The space $SS_{\gamma,m}^{a,b,\beta}$

It is defined as,

$$SS_{\gamma,m}^{a,b} = \left\{\phi : \phi \in E_+ \,/\, \sigma_{l,k,p}\phi(t,x) = \sup_{I_1}\left|t^l D_t^k D_x^p \phi(t,x)\right| \le C_{k,p,\mu}(m+\mu)^l\, l^{l\gamma}\right\} \tag{3.4}$$

For any $\mu > 0$ where m is the constant, depending on the function ϕ.

e) The space $SS^{a,b,\beta,n}$

This space is given by

$$SS^{a,b,\beta,n} = \left\{\phi : \phi \in E_+ \,/\, \rho_{l,k,p}\phi(t,x) = \sup_{I_1}\left|t^l D_t^k D_x^p \phi(t,x)\right| \le C_{l,p,\delta}(n+\delta)^k\, k^{k\beta}\right\} \tag{3.5}$$

For any $\delta > 0$ where n the constant is depends on the function ϕ.

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f) The space $SS_{\gamma,m}^{a,b,\beta,n}$

This space is defined by combining the conditions in (3.4) and (3.5).

$$SS_{\gamma,m}^{a,b,\beta,n} = \Big\{ \phi : \phi \in E_+ \, / \, \xi_{l,k,p}\phi(t,x) = \sup_{I_1} \left| t^l D_t^k D_x^p \phi(t,x) \right| \\ \le C_{\mu\delta} (m+\mu)^l (n+\delta)^k . l^{l\gamma} k^{k\beta} \Big\} \tag{3.6}$$

IV. Results on Countable Unions-Type Space

Proposition 4.1: If $m_1 < m_2$ then $SS_{\gamma,m_1}^{a,b} \subset SS_{\gamma,m_2}^{a,b}$. The topology of $SS_{\gamma,m_1}^{a,b}$ is equivalent to the topology induced on $SS_{\gamma,m_1}^{a,b}$ by $SS_{\gamma,m_2}^{a,b}$

$$i.e \;\; T_{\gamma,m_1}{}^{a,b} \sim T_{\gamma,m_2}{}^{a,b} \,/\, SS_{\gamma,m_1}^{a,b}$$

Proof: For $\phi \in SS_{\gamma,m_1}^{a,b}$ and $\delta_{l,k,p}(\phi) \le C_{k,\mu}(m_1+\mu)^l \, l^{l\gamma}$

$$\le C_{k,\mu,p}(m_2+\mu)^l \, l^{l\gamma} \quad \text{Thus, } SS_{\gamma,m_1}^{a,b} \subset ss_{\gamma,m_2}^{a,b}$$

The space $SS_{\gamma,}^{a,b}$ can be expressed as union of countable normed spaces.

Proposition 4.2: $SS_{\gamma}^{a,b} = \bigcup_{i=1}^{\infty} SS_{\gamma,m_1}^{a,b}$ and if the space $SS_{\gamma}^{a,b}$ is equipped with strict inductive limit topology $S_{a,b,m}$ defined by injective map from $SS_{\gamma,m_1}^{a,b}$ to $SS_{\gamma}^{a,b}$ then the sequence $\{\phi_n\}$ in $SS_{\gamma}^{a,b}$ converges to zero.

Proof: we show that $SS_{\gamma}^{a,b} = \bigcup_{i=1}^{\infty} SS_{\gamma.m_1}^{a,b}$

Clearly $\bigcup_{i=1}^{\infty} SS_{\gamma.m_1}^{a,b} \subset SS_{k}^{a,b}$ for proving the other inclusion, let $\phi \in SS_{\gamma}^{a,b}$ then

$$\delta_{l,k,p}(\phi(t,x)) = \sup_{I_1} \left| t^l D_t^k D_x^p \; \phi_n(t,x) \right| \\ \le C_{k,p} A^l l^{l\gamma}, \tag{4.1}$$

where A is some positive constant, choose an integer $m = m_A$ and $\mu = 0$ such that $C_{k,p}A^l \le C_{k,p}(m+\mu)^l$.

Then (4.1) we get $\phi \in SS_{\gamma,m_1}^{a,b}$ implying that $SS_{\gamma}^{a,b} = \bigcup_{i=1}^{\infty} SS_{\gamma,m_1}^{a,b}$

Proposition 4.3: If $\gamma_1 < \gamma_2$ and $\beta_1 < \beta_2$ then $SS_{\gamma_1}^{a,b,\beta_1} \subset SS_{\gamma_2}^{a,b,\beta_2}$ and the topology of $SS_{\gamma_i}^{a,b,\beta_i}$ is equivalent to the topology induced on $SS_{\gamma_1}^{a,b,\beta_1}$ by $SS_{\gamma_2}^{a,b,\beta_2}$.

Proof: Let $\phi \in SS_{\gamma_1}^{a,b,\beta_1}$

$$\xi_{l,k,p}(\phi) = \sup_{I_1} \left| t^l D_t^k D_x^p \phi(t,x) \right|$$

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$$\le CA^l l^{l\gamma_1} B^k k^{k\beta_1}$$

$$\le CA^l l^{l\gamma_2} . B^p k^{p,\beta_2} \qquad \text{where} l, k, p = 0,1,2,3$$

Hence $\phi \in SS_{\gamma_2}^{a,b,\beta_2}$. Consequently, $SS_{\gamma_1}^{a,b,\beta_1} \subset SS_{\gamma_2}^{a,b,\beta_2}$. The topology of $SS_{\gamma_1}^{a,b,\beta_1}$

Is equivalent to the topology $T_{\gamma_2}^{a,b,\beta_2} / SS_{\gamma_2}^{a,b,\beta_2}$

It is clear from the definition of topologies of these spaces.

Proposition 4.4: $SS^{a,b} = \overset{\infty}{\underset{\gamma_i\beta_i=1}{U}} SS_{\gamma_i}^{a,b,\beta_i}$ and if the space $SS^{a,b}$ is equipped with the strict $SS^{a,b}$ inductive limit topology defined by the injective maps from $SS_{\gamma_i}^{a,b,\beta_i}$ to $SS^{a,b}$ then the sequence $\{\phi_n\}$ in $SS^{a,b}$ converges to zero iff $\{\phi_n\}$ is contained in some $SS_{\gamma_i}^{a,b,\beta_i}$ and converges to zero.

Proof: $SS^{a,b} = \overset{\infty}{\underset{\gamma_i\beta_i=1}{U}} SS_{\gamma_i}^{a,b,,\beta_i}$

Clearly $\overset{\infty}{\underset{\gamma_i\beta_i\ 1=}{U}} SS_{\gamma_i}^{a,b,\beta_i} \subset SS^a$

For proving other inclusion, let $\phi(t,x) \in SS^{a,b}$ then

$$\eta_{l,k,p}(\phi) = \sup_{I_1} \left| t^l D_t^k D_x^p \phi(t,x) \right|,$$

is bounded by some number. We can choose integers γ_m and β_m such that

$$\eta_{l,k,p}(\phi) \le C\, A^l l^{l,\gamma} B^{k,m}, k^{k,\beta,m}$$

$\therefore \phi \in SS_{\gamma_i}^{a,b,\beta_i}$ for some integer γ_i and β_i

Hence $SS^{a,b} \subset \overset{\infty}{\underset{\gamma_i\beta_i=1}{U}} SS_{\gamma_i}^{a,b,\beta_i}$ Thus $SS^{a,b} = \overset{\infty}{\underset{\gamma_i\beta_i=1}{U}} SS_{\gamma_i}^{a,b,\beta_i}$

V. Inversion and Uniqueness Theorems

Theorem 5.1: (Inversion) If $\{2DCSST\ f(t,x)\}(s,w)$ is canonical sine-sine transform of $f(t,x)$ then inverse of transform is given by

$$f(t,x) = -\sqrt{\frac{2\pi i}{b}}\sqrt{\frac{2\pi i}{b}}\, e^{\frac{-i}{2}\left(\frac{a}{b}\right)t^2} e^{\frac{-i}{2}\left(\frac{a}{b}\right)x^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right) e^{\frac{-i}{2}\left(\frac{d}{b}\right)s^2} e^{\frac{-i}{2}\left(\frac{d}{b}\right)w^2} \{2DCSST\ f(t,x)\}(s,w)\,ds\,dw$$

Theorem 5.2: (Uniqueness) If $\{2DCSST\ f(t,x)\}(s,w)$ and $\{2DCSST\ g(t,x)\}(s,w)$ are 2D canonical sine-sine transform and $\sup pf \subset s_a$ and s_b also $\sup p\ g \subset s_a and\ \ s_b$

Where $s_a = \{t : t \in R^n,\ \ |t| \le a, a > 0\}$ and $s_b = \{x : x \in R^n,\ \ |x| \le b, b > 0\}$

If $\{2DCSST\ f(t,x)\}(s,w) = \{2DCSST\ g(t,x)\}(s,w)$

then, $f = g$ in the sense of equality in $D'(I)$

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Proof: By inversion theorem

$$f-g=$$
$$-e^{\frac{-i}{2}\left(\frac{a}{b}\right)t^2}e^{\frac{-i}{2}\left(\frac{a}{b}\right)x^2}\left[\left(\sqrt{\frac{2\pi i}{b}}\sqrt{\frac{2\pi i}{b}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}e^{\frac{-i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{-i}{2}\left(\frac{d}{b}\right)w^2}\sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right)\{2DCSST\ f(t,x)\}(s,w)\,dsdw,\right)\right.$$

$$\left.-\left(\sqrt{\frac{2\pi i}{b}}\sqrt{\frac{2\pi i}{b}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}e^{\frac{-i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{-i}{2}\left(\frac{d}{b}\right)w^2}\sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right)\{2DCSST\ g(t,x)\}(s,w)\,dsdw,\right)\right]$$

$$\therefore f-g=-\sqrt{\frac{2\pi i}{b}}\sqrt{\frac{2\pi i}{b}}e^{-\frac{i}{2}\left(\frac{a}{b}\right)t^2}e^{-\frac{i}{2}\left(\frac{a}{b}\right)x^2}\int_{-\infty}^{\infty}e^{-\frac{i}{2}\left(\frac{d}{b}\right)s^2}e^{-\frac{i}{2}\left(\frac{d}{b}\right)s^2}\sin\left(\frac{s}{b}x\right)\sin\left(\frac{w}{b}x\right)$$
$$\left[\{2DCSST\,f(t,x)\}-\{2DCSST\,g(t,x)\}\right]dsdw$$

Thus $f=g$ in $D'(I)$

VI. Modulation Theorems for Canonical Sine-Sine Transform

Theorem 6.1: If $\{2DCSST\ f(t,x)\}(s,w)$ is canonical sine-sine transform of $f(t,x)$ then

$$\{2DCSST\cos\mu t\ f(t,x)\}(s,w)$$
$$=\frac{e^{-\frac{i}{2}(\mu^2bd)}}{2}\left[e^{-i(s\mu d)}\{2DCSST\ f(t,x)\}(s+\mu b,w)+e^{i(\mu sd)}\{2DCSST\ f(t,x)\}(s-\mu b,w)\right]$$

Proof: Definition of two dimensional canonical sine-sine transform $f(t,x)$ is

$$\{2DCSST\ f(t,x)\}(s,w)$$
$$=-\frac{1}{\sqrt{2\pi ib}}\frac{1}{\sqrt{2\pi ib}}e^{\frac{i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{i}{2}\left(\frac{d}{b}\right)w^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right)e^{\frac{i}{2}\left(\frac{a}{b}\right)t^2}e^{\frac{i}{2}\left(\frac{a}{b}\right)x^2}f(t,x)\,dxdt$$

$$\{2DCSST\cos\mu t\ f(t,x)\}(s,w)$$

$$=-\frac{1}{\sqrt{2\pi ib}}\frac{1}{\sqrt{2\pi ib}}e^{\frac{i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{i}{2}\left(\frac{d}{b}\right)w^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sin\left(\frac{s}{b}t\right)\sin\left(\frac{w}{b}x\right)\cos\mu t\,e^{\frac{i}{2}\left(\frac{a}{b}\right)t^2}e^{\frac{i}{2}\left(\frac{a}{b}\right)x^2}f(t,x)\,dxdt$$

$$=-\frac{1}{2}\left[\frac{1}{\sqrt{2\pi ib}}\frac{1}{\sqrt{2\pi ib}}e^{\frac{i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{i}{2}\left(\frac{d}{b}\right)w^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sin\left(\frac{s+\mu b}{b}\right)t\sin\left(\frac{w}{b}x\right)e^{\frac{i}{2}\left(\frac{a}{b}\right)t^2}e^{\frac{i}{2}\left(\frac{a}{b}\right)x^2}f(t,x)\,dxdt\right.$$

$$\left.+\frac{1}{\sqrt{2\pi ib}}\frac{1}{\sqrt{2\pi ib}}e^{\frac{i}{2}\left(\frac{d}{b}\right)s^2}e^{\frac{i}{2}\left(\frac{d}{b}\right)w^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\sin\left(\frac{s-\mu b}{b}\right)t\sin\left(\frac{w}{b}x\right)e^{\frac{i}{2}\left(\frac{a}{b}\right)t^2}e^{\frac{i}{2}\left(\frac{a}{b}\right)x^2}f(t,x)\,dxdt\right]$$

$$=\frac{1}{2}\left[e^{-i(s\mu d)}e^{\frac{-i}{2}(\mu^2bd)}\{2DCSST\ f(t,x)\}(s+ub,w)+e^{i(s\mu d)}e^{\frac{-i}{2}(\mu^2bd)}\{2DCSST\ f(t,x)\}(s-ub,w)\right]$$

$$\{2DCSST\cos\mu t\ f(t,x)\}(s,w)$$
$$=\frac{e^{-\frac{i}{2}(\mu^2bd)}}{2}\left[e^{-i(s\mu d)}\{2DCSST\ f(t,x)\}(s+\mu b,w)+e^{i(\mu sd)}\{2DCSST\ f(t,x)\}(s-\mu b,w)\right]$$

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Theorem 6.2 If $\{2DCSST\ f(t,x)\}(s,w)$ is canonical sine-sine transform of $f(t,x)$ then

$$\{2DCSST \sin \mu t\ f(t,x)\}(s,w) =$$
$$\frac{ie^{-\frac{i}{2}(\mu^2 bd)}}{2}\left[e^{-i(s\mu d)}\{2DCCST\ f(t,x)\}(s+\mu b,w) - e^{i(\mu s d)}\{2DCCST\ f(t,x)\}(s-\mu b,w)\right]$$

Theorem 6.3 If $\{2DCSST\ f(t,x)\}(s,w)$ is canonical sine-sine transform of $f(t,x)$ then

$$\{2DCSSTe^{i\mu t}\ f(t,x)\}(s,w)$$
$$= \frac{e^{-\frac{i}{2}(\mu^2 bd)}}{2}\left[e^{-i(s\mu d)}\left(\{2DCSST\ f(t,x)\}(s+\mu b,w) - \{2DCCST\ f(t,x)\}(s+\mu b,w)\right)\right.$$
$$\left.+ e^{i(s\mu d)}\left(\{2DCSST\ f(t,x)\}(s-\mu b,w) + \{2DCCST\ f(t,x)\}(s-\mu b,w)\right)\right]$$

Proof: Since $\{2DCSST\, e^{i\mu t}\ f(t,x)\}(s,w) = \{2DCSST(\cos \mu t + i \sin \mu t)\ f(t,x)\}(s,w)$

$$\{2DCSST\, e^{i\mu t}\ f(t,x)\}(s,w) = \{2DCSST \cos \mu t\ f(t,x)\}(s,w) + i\{2DCSST \sin \mu t\, f(t,x)\}(s,w)$$

$$-\frac{e^{-\frac{i}{2}(\mu^2 bd)}}{2}\left[e^{-i(s\mu d)}\{2DCCST\ f(t,x)\}(s+\mu b,w) - e^{i(s\mu d)}\{2DCCST\ f(t,x)\}(s-\mu b,w)\right]$$

$$\frac{e^{-\frac{i}{2}(\mu^2 bd)}}{2}\left[e^{-i(s\mu d)}\{2DCSST\ f(t,x)\}(s+\mu b,w) + e^{i(s\mu d)}\{2DCSST\ f(t,x)\}(s-\mu b,w)\right.$$
$$\left.-e^{-i(s\mu d)}\{2DCCST\ f(t,x)\}(s+\mu b,w) + e^{i(s\mu d)}\{2DCSCT\ f(t,x)\}(s-\mu b,w)\right]$$

$$\{2DCSSTe^{i\mu t}\ f(t,x)\}(s,w) = \frac{e^{-\frac{i}{2}(\mu^2 bd)}}{2}\left[e^{-i(s\mu d)}\left(\{2DCSST\ f(t,x)\}(s+\mu b,w) - \{2DCCST\ f(t,x)\}(s+\mu b,w)\right)\right.$$
$$\left.+ e^{i(s\mu d)}\left(\{2DCSST\ f(t,x)\}(s-\mu b,w) + \{2DCCST\ f(t,x)\}(s-\mu b,w)\right)\right]$$

VII. Conclusion

In this paper 2D canonical sine–sine transform is generalized in the distributional sense. Uniqueness theorem is proved and various testing functions specs defined by using Gelfand-shilov technique, topology properties are discussed. And lastly modulation theorems are proved.

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