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Ultra-hyperbolic approach to some multi-dimensional inverse problems

By Takeishi SUZUKI (Tokyo Metropolitan Univ.)

81. Introduction. Our aim is to describe the basic idea of [162] to show the uniqueness of multi-dimensional inverse problems of some kind.

To fix the idea, let us recall the work [131] by A. Pierce in 1979, where uniqueness of some parabolic inverse problem was established via the theory of Gelfand-Levitan [62]. Namely, for \((p, \varphi, \lambda)\) and \((q, \psi, \mu)\) in \(C^1[0,1] \times \mathbb{R} \times \mathbb{R}\), let \(u = u(x,t)\) and \(v = v(x,t)\) solve

\[
\begin{align*}
&u_t - uu_x = p(x)u \quad (0 < x < 1, \ 0 < t < T), \quad u \big|_{x=0} = 0 \quad (0 < x < 1), \\
&\left. -u_x + \lambda u \right|_{x=1} = f(t) \quad (0 < x < T)
\end{align*}
\]

and

\[
\begin{align*}
&v_t - vv_x = q(x)v \quad (0 < x < 1, \ 0 < t < T), \quad v \big|_{x=0} = 0 \quad (0 < x < 1), \\
&\left. -v_x + \mu v \right|_{x=1} = f(t) \quad (0 < x < T)
\end{align*}
\]

respectively. Then, the identity
\[ (1.3) \quad u - u \mid_{x=1} = 0 \quad (0 < x < 1) \]

implies

\[ (8.1.4) \quad (p, i, J) = (p, k, h), \]

provided that \( f \neq 0 \).

The proof is carried out in the following manner. First, in the case of \( f \neq 0 \) the function \( \varphi(t) = u \mid_{x=1} \) \((0 < x < 1)\) determines the spectral characteristics \( \{ \lambda_j, g_j \}_{j=0}^\infty \) of \( A = Ap(k, h) \), the differential operator

\[ -\frac{d^2}{dx^2} + p(x) \] under the boundary condition \( (-\frac{d}{dx} + b) \mid_{x=0} = (\frac{d}{dx} + h) \mid_{x=1} = 0. \) Then, the conclusion \((1.4)\) follows from the Gel'fand-Levitan theory.

Here, \( \{ \lambda_j \}_{j=0}^\infty \) \((-\infty < \lambda_0 < \lambda_1 < \cdots \) denotes the set of eigenvalues of \( A = Ap(k, h) \), while \( g_j \) is the norming constant; \( g_j = \| g_j \|_{L^2(0, 1)}^2 \), where \( g_j = g_j(x) \) is the eigenfunction of \( A \) corresponding to \( \lambda_j \) and normalized as \( g_j \mid_{x=0} = 1. \) The Gel'fand-Levitan theory implies that the spectral characteristics \( \{ \lambda_j, g_j \} \) determine the operator \( Ap(k, h) \).

Motivated by this, R. Hurayama and the author have studied the equation.
\[
(1.5) \quad \begin{cases}
    u_t - u_{xx} = p(x) u & (0 < x < 1, 0 < t < T), \\
    u(x, 0) = a(x) & (0 < x < 1)
\end{cases}
\]

\[
- u_x + H u \big|_{x=0} = u_x + H u \big|_{x=1} = 0 \quad (0 < t < T)
\]

to determine \((p, l, H, a) \in C^4(0, 1) \times \mathbb{R} \times L^2(0, 1)\) through the boundary value \(f_j(t) = u|_{x=j} \ (0 < t < T; j=0, 1)\) of the solution \([17], [97], [131]\).

For this problem the uniqueness holds in a generic situation.

There, we noticed the idea of Gelfand-Levitan to introduce the following deformation formula

\[
(1.6) \quad g(x, \lambda; b, j) = g(x, \lambda; b, h) + \int_0^x K(x, y; b, j; p, h) g(y, \lambda; b, h) \, dy \quad (0 \leq \lambda \leq 1)
\]

for \(x \in \mathbb{R}\). Here, \(g = g(x, \lambda; b, h)\) denotes the solution of

\[
(1.7) \quad \left( -\frac{d^2}{dx^2} + p(x) \right) g = \lambda g \ (0 \leq \lambda \leq 1) \quad \text{with} \quad g|_{x=0} = 1 \quad \text{and} \quad g|_{x=1} \mu = h.
\]

The kernel \(K(x, y; b, h) = K(x, y; b, j; p, h)\) is independent of \(\lambda\) and is characterized as the solution of the hyperbolic boundary value problem

\[
(1.8) \quad \begin{cases}
    k_{11} - k_{12} + p(y) k_{21} = g(x) k_{11} \quad \text{(in } S), \\
    k_{12}(x, 0) = H_k(x, 0) \quad (0 \leq x \leq 1), \\
    k_{12}(x, x) = (y - e) + \frac{1}{2} \int_0^x (g(s) - p(s)) \, ds \quad (0 \leq x \leq 1),
\end{cases}
\]
where \( \Omega = \{(x,y) \mid 0 < y < x < 1\} \).

This method of integral transformation, sometimes referred to as the transmission theory (Carroll [5], e.g.), has been useful in the study of one-dimensional inverse problems (E142). However, it seemed to be quite difficult to extend the idea to multi-dimensional cases.

In 1986, the author showed a uniqueness result for those cases with analytic coefficients, utilizing Holmgren's theorem (E151). Now we have established it within the \( C^0 \)-category, noting some key identity. This is the object of the present article.

We refer to some works by the Novikov school for other approaches to multi-dimensional inverse problems, especially for hyperbolic equations (Bukhgeim-Jahno [27], Romanov [27], Bukhgeim-Klibanov [31]).

Henceforth, \( \Omega \subset \mathbb{R}^n \) denotes a bounded domain whose boundary \( \partial \Omega \) is smooth. The differential operator \( \mathcal{L} u = \nabla \cdot (a \nabla u) + cu \) is symmetric, uniformly elliptic, and second order with smooth real coefficients \( a = a(x) \) and \( c = c(x) \) on \( \partial \Omega \), and \( d = d(x) \) is a given smooth function on \( \partial \Omega \). To fix the idea, consider the parabolic problem

\[
\begin{align*}
\frac{\partial u}{\partial t} - \mathcal{L} u &= 0 \quad (x \in \Omega, 0 < t < T), \\
\frac{\partial u}{\partial t} - (\frac{\partial}{\partial x} + d) u &= f \quad (0 < x < 1) \\
\end{align*}
\]
where \( \partial / \partial \nu = \sum_{i=1}^{n} \alpha_i \partial / \partial x_i \) denotes the differentiation along the co-normal vector, \( \nu = (\nu_i) \) being the outer unit normal vector on \( \partial \Omega \).

Regarding the function \( F = F(\nu, t) \) as an input, we wish to determine the coefficients \( (a, c, d) \) through the boundary output \( g = g(\nu, t) = u(\nu, t) \) \( (\nu \in \Gamma, 0 < t < T) \), where \( \nu \in \partial \Omega \) with \( |\nu| > 0 \). Our conclusion assures a generic uniqueness result provided that the input \( F = F(x, t) \) is given in the same area as the output \( g \), that is, \( k \neq 0 \) and \( \text{supp } f \subset \Gamma \). Thus, we can extend the result by A. Pierce to the multi-space dimensional case.

A similar phenomenon can be seen for the interior input-output problem. Namely, in the parabolic problem

\[
\begin{align*}
\frac{\partial u}{\partial t} - Du &= f(x) k(t) \quad (x \in \Omega, 0 < t < T), \\
\frac{\partial u}{\partial \nu} &= 0 \quad (x \in \partial \Omega), \\
\left( \frac{\partial^2 u}{\partial x_i \partial x_j} + d \right) u &= 0 \quad (0 < t < T),
\end{align*}
\]

the output \( g = u|_{\Gamma} \) \( (0 < t < T) \) determines generically \( (a, c, d) \), provided that the input \( F = f(x) k(t) \) is taken as \( k \neq 0 \) and \( \text{supp } f \subset \Omega \), where \( \Omega \subset \Delta \) is a non-empty open set. However, the cases where inputs and outputs are taken in different areas remain as problems in future.
Reduction to the spectral problem. To state the result, let \( P \) and \( \Theta \) be second order symmetric uniformly elliptic differential operators and \( \alpha \) and \( \beta \) be smooth functions on \( \Omega \). We suppose that these are temporally homogeneous and depend only on space variables. Given a family of inputs \( F_e = F_e(t) \) \( (t \in S) \), we consider the parabolic equations

\[
(2.1) \quad \frac{\partial u_e}{\partial t} - Pu_e = 0 \quad (x \in \Omega, 0 < t < T), \quad u_e \big|_{t=0} = 0 \quad (x \in \Omega),
\]

\[
\left. \frac{\partial^2 u_e}{\partial x^2} + \alpha \right|_{\partial \Omega} = F_e \quad (0 < t < T),
\]

and

\[
(2.2) \quad \frac{\partial v_e}{\partial t} - Qv_e = 0 \quad (x \in \Omega, 0 < t < T), \quad v_e \big|_{t=0} = 0 \quad (x \in \Omega),
\]

\[
\left. \frac{\partial^2 v_e}{\partial x^2} + \beta \right|_{\partial \Omega} = F_e \quad (0 < t < T).
\]

For a given area \( P \subset \Omega \) with \( |P| > 0 \), we suppose that

\[
(2.3) \quad v_e - u_e \big|_{P} = 0 \quad (0 < t < T, e \in S).
\]

We wish to establish some criterion for (2.3) to imply the uniqueness,

\[
(2.4) \quad (Q, \beta) = (P, \alpha).
\]
For the moment, we drop the suffix \( \nu \in \mathbb{S} \). Homogeneous \( \partial_j \psi \), \( \partial_j \psi \), \( \partial_j \psi \), \( \partial_j \psi \) denote the eigenvalues and eigenfunctions of \(-P_\eta\), the differential operator \(-P\) with \( \left( \frac{\partial^2}{\partial t^2} + \mathcal{O} \right) \psi = 0 \) and \(-Q_\eta\), the differential operator \(-Q\) with \( \left( \frac{\partial^2}{\partial t^2} + \mathcal{O} \right) \psi = 0 \), respectively. Here, \(-\infty < \lambda_1 < \lambda_2 \leq \cdots \to \infty\) \(-\infty < \mu_1 < \mu_2 \leq \cdots \to \infty\), and \( \| \psi_j \|_{L^2(\Omega)} = \lambda_j^{1/2} \| \psi_j \|_{L^2(\Omega)} = 1 \). Then,

\[
G(x, y; t) = \sum_j e^{-\lambda_j^2 t} \phi_j(x) \phi_j(y)
\]

is nothing but the Green function of \(-\partial^2_t + \mathcal{O}\), and the solution \(u = u(x, t)\) of (2.1) is given as

\[
u(x, t) = \int_0^t dt \int_\Omega \frac{\partial}{\partial \eta} G(x, \zeta; t - \tau) F(\zeta, \tau)
\]

\[
= \int_0^t \tau(x, t - \tau) R(\tau) dt,
\]

where

\[
(2.5) \quad \tau(x, t) = \sum_j e^{-\lambda_j^2 t} \phi_j(x) \int_\Omega \phi_j(\zeta) f(\zeta) d\zeta
\]

because of \( F(x, t) = f(x) R(t) \). Similarly, we have

\[
u(x, t) = \int_0^t \delta(x, t - \tau) R(\tau) dt
\]
with

\begin{equation}
S_{u,t} = \sum_i e^{-\mu_t^i} \nu_t^i \int_{\mathbb{R}} \nu_t^i (x) g(x) dx,
\end{equation}

so that \((2.3)\) reads as

\begin{equation}
\int_0^t S(u, t-c) h(c) dc = \int_0^t f(u, t-c) h(c) dc \quad (\mathbb{R}^+, 0 < t < 1).
\end{equation}

Assuming

\begin{equation}
\text{Re} \neq 0,
\end{equation}

we arrive at

\begin{equation}
S(u, t) = r(u, t) \quad (\mathbb{R}^+, 0 < t < 1),
\end{equation}

which extends to the full-range \( t \in (0, \infty) \) by analytic continuation:

\begin{equation}
S(u, t) = r(u, t) \quad (\mathbb{R}^+, 0 < t < \infty).
\end{equation}

Here, we compare the behavior as \( t \to +\infty \) of both sides of \((2.8)\).
To this end we introduce the sets $T_\lambda = \{ j \mid x_j = \lambda \}$ and $\mathcal{L}_\lambda = \{ j \mid y_j = \lambda \}$ for real numbers $\lambda \in \mathbb{R}$, and impose that

\[(A.2) \quad \text{for each } \lambda \in \mathbb{R}, \quad \text{with } \mathcal{L}_\lambda \neq \emptyset, \quad \text{the matrices } (A_{\lambda j} f_k)_{j,k} \text{ and } \quad \text{and } (B_{\lambda j} f_k)_{j,k} \text{ are of full-rank, respectively, where } \quad B_{\lambda j} f_k = \int_{x_j} g(x) f_k(x) \, dx \quad \text{and} \quad B_{\lambda j} = \int_{x_j} g(x) \, dx.

Then, in particular for each $\lambda \in \mathbb{R}$ with $\mathcal{L}_\lambda \neq \emptyset$, there exist some $j \in T_\lambda$ and $l \in \mathcal{L}_\lambda$ such that $\mathcal{A}_{jl} \neq 0$ and so is true for $\mathcal{L}_\lambda$ and $\mathcal{B}_{jl}$. On the other hand, by virtue of Calderón's uniqueness theorem (14.2), we have the following.

**Proposition.** Each of $E_{jl}^T_{j \in T_\lambda}$ and $E_{jl}^L_{j \in \mathcal{L}_\lambda}$ forms a system of linearly independent functions on $\mathbb{R}$.

In fact, $E_{jl}^T_{j \in T_\lambda}$ satisfy the same equation $(2+\lambda) \gamma = 0$ in $\mathbb{R}$. Therefore, supposing $g = \sum_{j \in T_\lambda} a_j \gamma_j = 0$ on $\mathbb{R}$ for real constants $a_j$ $(\ell \in \mathbb{N})$, we have $g|_\mathbb{R} = \sum_{j \in T_\lambda} a_j \gamma_j|_\mathbb{R} = 0$ and hence $g = 0$ near $\mathbb{R}$ by Calderón's theorem. Now the unique continuation property assures us of $g = 0$ in $\mathbb{R}$ and hence $a_j = 0$ $(j \in T_\lambda)$.

Therefore, for each $\lambda$ with $T_\lambda \neq \emptyset$ there exists some $l$ such that
\[ \sum_{j \in J_A} \gamma_j(x) a_{je} = 0 \quad \text{on } \Gamma \quad \text{and so is true for } \xi_X \text{ and } \sum_{j \in J_X} \gamma_j(x) b_{je}. \]

In particular, (2.8) implies that

\[ \{ y | j \in J_A \} = \{ y | j \in J_X \} \]

and also

\[ \sum_{j \in J_A} \gamma_j(x) a_{je} = \sum_{j \in J_X} \gamma_j(x) b_{je} \quad (x \in \Gamma, \text{ } a \in S). \]

Again, the assumption (A2) improves (2.9) as

\[ J_A = \Lambda_X \quad (x \in \mathbb{R}) \]

via Proposition and (2.10). Furthermore, (2.10) reduces to the relation

\[ g_j(x) = \sum_{k \in L_A} g_{jk} \gamma_k(x) \quad (x \in \Gamma, j \in J_A) \]

for some real numbers \( \{ g_{jk} \} \).

Henceforth, we suppose the following important assumption:
(A.2) \[ \text{supp } f \subseteq C \cap (l < s^r) \]

Then, we have

\[ A_{je} = \int_p g_j(s) f_e(s) \text{d}^3 \]

and hence can substitute (2.12) into (2.10). Using Proposition, we get

\[ \sum_{j,m \in J_a} \tilde{T}_{jm} \tilde{f}_{jm} B_{me} = B_{ke} \quad (k + l, l < s^r) \]

or

\[ \tilde{T} (\tilde{f}_{j,k}) (\tilde{f}_{j,k}) = (\tilde{f}_{j,k}) \]

by (A.2). Hence \( \{ \tilde{T}_{j,k} \}_{j,k \in J_a} \) forms an orthonormal system in \( L^2(\mathbb{R}^3) \)

where \( \tilde{T}_{j,k} = \sum_{k \in J_a} \tilde{T}_{jk} \). Without loss of generality, we may suppose that

(2.13) \[ \tilde{T}_{j,k} = \lambda_j \text{ and } \tilde{T}_{j,k} (x) = g_j(x) (x \in X) \text{ for all } j. \]
3. Iso-spectral deformation. Now, we shall show that the condition (2.12) implies the uniqueness

\begin{equation}
(\lambda, \beta) = (\mu, \alpha),
\end{equation}

which corresponds exactly to Gel'fand-Levinson's uniqueness result in one-space dimension. The author has shown the fact in a rather special case in [15] of analytic coefficients operators. An extension to \( C^\infty \) coefficients operators has been performed by A. Nachman, J. Sylvester and G. Uhlmann in [10] motivated by Borg-Levinson's work ([13], [18]), for \( -P = -\Delta + p(x) \), \( -Q = -\Delta + q(x) \), \( \beta = x = 0 \) and \( \tau = 2\pi \) through a function theoretic method. Here, we take a different approach of deformation formula described in [1] for one-space dimensional case.

The formula (1.6) reads as

\begin{equation}
\gamma(x, \lambda) = \tilde{\gamma}(x, \lambda) + \int_0^1 H(x-y) K(y, \lambda) \gamma(y, \lambda) dy,
\end{equation}

where \( H = H(x) \) is the Heaviside function. Then, the commutation

\[ \frac{d}{dx}, H \] will produce the \( \delta \)-function and the deformation (1.6) is achieved. In spite that there is no reasonable extension of the Heaviside function in multi-dimensional spaces, the above relation means
(3.2) \[ \phi_j = (1 + K) \phi_j \]

for the iso-spectral case \( \phi_j(y) = y_j(y) \) (j=1,2,---). The operator \( K \) is formally an integral operator with the kernel

(3.3) \[ K(x,y) = \sum_j \{ y_j(x) - y_j(y) \} \phi_j(y). \]

In view of (3.2), \( K = K(x,y) \) has the Heaviside-function like discontinuity on the diagonal \( D = \{(x,x) | x \in \mathbb{R}\} \) when the space-dimension is one.

For the moment, we shall develop a formal theory which will be justified later. Hence we note the following key "identity"

(3.5') \[ K(x,y) = \sum_j \{ y_j(x) - y_j(y) \} \phi_j(y) = \sum_j y_j(x) \int \phi_j(y) - \phi_j(y). \]

In fact, we have

\[ \sum_j y_j(x) \phi_j(y) = \sum_j y_j(x) \phi_j(y) = \delta(x-y). \]

The "function" \( K^* = K^*(x,y) = \sum_j y_j(x) \phi_j(y) \) satisfies the ultra-hyperbolic equation
\[ \Delta K^* = 0, \]

where

\[ \Delta = -Q_x + B_y. \]

In fact, we have \( y_j = y_j \quad (j = 1, 2, \ldots) \). Hence

\[ \Delta K = 0 \quad (x \neq y) \]

by \( K(x, y) = K^*(x, y) - f(x - y) \). On the other hand we have

\[ \left. K \right|_{p \times n} = \left. K \right|_{n \times p} = 0. \]

by \( g_j (x) = y_j (x) \quad (x \neq p, \ j = 1, 2, \ldots) \).

However, noting (3.7) we have

\[ \sum_j \left. Q_x^m K \right|_{p \times n} = \sum_j \left. B_y^m K \right|_{p \times n} = 0, \]

where \( m = 0, 1, 2, \ldots \). In other words,

\[ \sum_j \chi_j^m \eta_j^*(x) \{ g_j^*(y) - f_j^*(y) \} = 0 \quad (m = 0, 1, 2, \ldots; x \neq p, y \neq s). \]
From the "Weierstrass approximation theorem" we get

$$
\sum_{j \in \mathbb{Z}} g_j(x) \{ f_j(y) - f_j(y) \} = 0 \quad (x \in \mathcal{R}, y \in \mathbb{A})
$$

for every $x \in \mathcal{R}$. Again by Proposition in the previous section, we have $g_j \equiv g_j$ ($j=1, 2, \ldots$). Now, both of eigenvalues and eigenfunctions coincide, we arrive at $P_\mathcal{R} = \psi_\mathcal{R}$, which means that $Q = \mathcal{R}$ and $b = a$.

The above formal argument can be justified in the following way. First, for any given integer $k \geq 0$, we choose large numbers $\lambda$ and $\lambda$ so that

$$
L_s(x, y; \lambda) = \sum_j \{ f_j(x) - g_j(y) \} g_j(y)(y_j + \lambda)^{-s} \in C^k(\overline{\mathcal{R}_x \times \mathcal{R}_y}).
$$

Then,

$$
L(x, y) \equiv (-P_y + A)^s L_s(x, y; \lambda) \in C^k(\overline{\mathcal{R}_x} \rightarrow \mathcal{D}'(\mathcal{R}_y))
$$

is independent of $\lambda$ and $s$, and $L(L(x, y)) \in C^\infty(\overline{\mathcal{R}_x} \rightarrow \mathcal{D}'(\mathcal{R}_y))$

$L(\overline{\mathcal{R}_x \times \mathcal{R}_y})$ can be defined. Similarly, from the function
\[ H_{\nu} (x, y; \lambda) = \sum_{j} h_j (x) \left[ y_j (x) - y_j (y) \right] (x_j + \lambda)^{-5} \in C^0 (\overline{\Omega} \times \overline{\Omega}) \]

we can define

\[ M = M (x, y) \in C^0 (\overline{\Omega} \times \overline{\Omega}) \subset C (\Omega \times \Omega) \text{ through} \]

\[ M (x, y) \equiv (-Q_x + \lambda)^5 H_5 (x, y; \lambda). \]

Now the key identity (3.5) is justified as

\[ L (x, y) = M (x, y) \quad (=: K (x, y)) \quad \text{as } D (\Omega \times \Omega). \]

Namely, the distribution \( K = K (x, y) \in D (\Omega \times \Omega) \) has an \textit{uncertain} character. \( K (x, y) = L (x, y) \in C^0 (\overline{\Omega} \times \overline{\Omega}) \) and \( K (x, y) = M (x, y) \in C^0 (\overline{\Omega} \times \overline{\Omega}) \). By the hypothesis of iso-spectral:

\[ \lambda_j = \mu_j \quad (j = 1, 2, \ldots), \]

ultra-hyperbolic relation

\[ \Box K = 0 \]

holds in \( \Omega \times \Omega \setminus D \) and \( \Omega \times \Omega \setminus D \) as \( K = \lambda \) and \( K = M \), respectively. Where \( D = \{ (x, y) \mid x \in \Omega \} \). Hence from \( L \Omega \mid \nu = 0 \)

we obtain...
as elements in $\mathcal{C}^0(\overline{\Omega} \to \mathbb{R})$.

Here, we introduce the function

\[(3.9) \quad F_t(x, y) = \sum_j e^{-\lambda_j^+ t} \gamma_j(x) \{ g_j(y) - y_j(y) \} \in \mathcal{C}^0(\overline{\Omega} \times \overline{\Omega})\]

for $t > 0$. The key identity (3.5) deduces

\[(3.10) \quad F_t(x, y) = \sum_{m=0}^{\infty} \frac{t^m}{m!} \mathcal{Q}_x^m K(x, y) \quad \text{in } \mathcal{D}'(\overline{\Omega} \times \overline{\Omega}).\]

In fact, we have in $\mathcal{D}'(\overline{\Omega} \times \overline{\Omega})$ that

\[
F_t(x, y) = \sum_j \sum_m \frac{t^m}{m!} (-\lambda_j^+)^m \gamma_j(x) \{ g_j(y) - y_j(y) \}
\]

\[
= \sum_m \sum_j \frac{t^m}{m!} (-\lambda_j^+)^m \gamma_j(x) \{ g_j(y) - y_j(y) \},
\]

while

\[
\mathcal{Q}_x^m K(x, y) = \sum_j (-\lambda_j)^m \gamma_j(x) \{ g_j(y) - y_j(y) \}
\]

in $\mathcal{D}'(\overline{\Omega} \times \overline{\Omega})$ by (3.5). However, the right-hand side of (3.10) converges in $\mathcal{C}^0(\overline{\Omega} \to \mathcal{D}'(\overline{\Omega}))$ and hence (3.10) holds as
a relation there. Hence

\[(3.11)\quad f_t(x, y) = 0 \quad (0 < t < \infty, x \in \mathbb{R}, y \in \mathbb{R})\]

by \((3.8)\).

Comparing the behavior as \(t \to \infty\) and utilizing Proposition in the preceding section, we arrive at

\[(3.12)\quad f_j = g_j \quad (j = 1, 2, \ldots)\].

Then, \((Q, \Phi) = (Q, \Omega)\) follows.

References


[71] Isozaki, H., private communication


Note: An important remark has been given by H. Isozaki for multi-dimensional iso-spectral problems ([17]).