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and Nobukazu Otsuki**

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Introduction

As conjectured in [1], some spectral invariants of a closed partitioned manifold $M = M_0 \cup_{\Sigma} M_1$ with $M_0 \cap M_1 = \partial M_0 = \partial M_1 = \Sigma$ can be coded by the intersection geometry of the Cauchy data spaces along the partitioning hypersurface Σ of associated differential operators. The Yoshida-Nicolaescu Formula belongs to this program. It was proved in [16] in dimension 3 and subsequently generalized in [12] and modified by several authors (see e.g. [2], [3], [7], [8]). It expresses the spectral flow of a family of Dirac operators with the same principal symbol but continuously varying connections by the Maslov intersection index of the Cauchy data spaces.

A closer look at the presently available spectral flow formulas shows that they differ quite a bit in the kind and strength of the underlying assumptions and the substance of the claims made. It seems to us that our framework (based on standard functional analysis involving only elementary distribution theory) permits a wider applicability than rather deep means (like the symbolic calculus and approximation theory).

First of all, the Cauchy data spaces are treated in slightly different ways. On one side, the Cauchy data spaces are established as L^2 -closures of smooth

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sections over the partitioning hypersurface Σ , coming from the restriction to the boundary of all smooth solutions over one of the parts M_j of the partitioned manifold M . In the case of the Dirac operator, this Cauchy data space can be represented as the range of the L^2 -extension of the pseudo-differential Calderón projection and established as a Lagrangian subspace of the symplectic Hilbert space $L^2(-\Sigma) \dot{+} L^2(\Sigma)$ (for the somewhat delicate details see e.g. [4], pp. 75–104).

On the other side, the Cauchy data spaces can be established as subspaces of the symplectic Hilbert space $\beta := D_{\max}/D_{\min}$ of natural boundary values, i.e. the boundary values of sections belonging to the maximal domain $D_{\max}$ of the operator (so in [2], [3], see also [11]). One can embed β as a non-closed subspace into the distribution space $H^{-1/2}(-\Sigma) \dot{+} H^{-1/2}(\Sigma)$. This treatment of the Cauchy data spaces is independent of pseudo-differential analysis and has several conceptual and technical advantages: the arguments work for any symmetric elliptic differential operator of first order which satisfies a weak unique continuation property and admits an extension defining a self-adjoint Fredholm operator. Moreover, no product structures are required near the boundary. Finally, the space β is basic and most suitable for a short and general proof of the closedness and the Lagrangian property of the Cauchy data spaces and the continuity of the corresponding transformation from symmetric operators to Lagrangian subspaces. As observed already in [14], establishing this continuity is the crucial step in proving spectral flow formulas.

In [2], this β -program was carried out by standard functional analysis arguments and without assuming regularity at the endpoints or differentiability of the curve of operators, or other supplementary technical assumptions. The result was a quite general spectral flow formula, and the present paper is a continuation of [2]. We show, also by standard arguments, that an additional continuous transformation can be obtained, at least in the case when all metric structures are product near the separating (or non-separating) hypersurface, namely from the Cauchy data spaces of the β -theory into the ‘conventional’ L^2 -theory. This gives a slight generalization and a new proof of the Yoshida–Nicolaescu Formula.

In Section 1 we address a fairly general situation in symplectic functional analysis and prove a ‘criss-cross’ reduction theorem for the Maslov index. In Section 2 we give a condensed version of the General Spectral Flow Formula of [2]. In Section 3 we connect the two preceding sections and give a new proof of the Yoshida–Nicolaescu Formula. In the Appendix we correct an erroneous description in [2], §§ 1.1–1.2, and add a lemma to be inserted at the end of § 1.2 in [2].

1. Criss-Cross Reduction of the Maslov Index

Let β and L be symplectic Hilbert spaces with symplectic forms ω_β and ω_L , respectively. Let

$$(1.1) \quad \beta = \beta_- \dot{+} \beta_+ \quad \text{and} \quad L = L_- \dot{+} L_+$$

be direct sum decompositions by transversal (not necessarily orthogonal) pairs of Lagrangian subspaces. We assume that there exist continuous, injective mappings

$$(1.2) \quad i_- : \beta_- \longrightarrow L_- \quad \text{and} \quad i_+ : L_+ \longrightarrow \beta_+$$

with dense images and which are compatible with the symplectic structures, i.e.

$$(1.3) \quad \omega_L(i_-(x), a) = \omega_\beta(x, i_+(a)) \quad \text{for all } a \in L_+ \text{ and } x \in \beta_-.$$

Let λ_0 be a fixed Lagrangian subspace of β . We denote the Fredholm Lagrangian Grassmannian of λ_0 by $\mathcal{FL}_{\lambda_0}(\beta)$. It is the space of all Lagrangian subspaces of β which make a Fredholm pair with λ_0 . Its topology is defined by the operator norm of the projections. Its fundamental group is $\mathbf{Z}$, and the mapping of the loops in $\mathcal{FL}_{\lambda_0}(\beta)$ onto $\mathbf{Z}$ is given by the Maslov index. It is an intersection index of the loop with the Maslov cycle

$$\mathcal{M}_{\lambda_0}(\beta) := \{\lambda \in \mathcal{FL}_{\lambda_0}(\beta) \mid \lambda \cap \lambda_0 \neq \{0\}\}.$$

By functional analytical means, the definition of the Maslov index can be extended unambiguously to all continuous curves in $\mathcal{FL}_{\lambda_0}(\beta)$ (see [2] and [3], inspired by [15]; we refer to [6] for various aspects of the Maslov index and also to [9], [10] for a cohomological treatment).

We are going to prove the following

THEOREM 1.1. *Under the assumptions (1.1), (1.2), and (1.3),*

(a) *we have a continuous mapping*

$$\tau : \mathcal{FL}_{\beta_-}(\beta) \longrightarrow \mathcal{FL}_{L_-}(L)$$

(b) *which maps the Maslov cycle of β_- into the Maslov cycle of L_- and*

(c) *preserves the Maslov index*

$$\text{mas}(\{\lambda_t\}_{t \in [0,1]}, \beta_-) = \text{mas}(\{\tau(\lambda_t)\}_{t \in [0,1]}, L_-)$$

for any continuous curve $[0, 1] \ni t \mapsto \lambda_t \in \mathcal{FL}_{\beta_-}(\beta)$.

We prove Theorem 1.1 in a series of small lemmata.

1.1. Definition of the mapping τ . We consider the direct sum

$$\mathcal{D} := \beta_+ \oplus L_- ,$$

where β and L are identified with subspaces of $\mathcal{D}$. Then we define the mapping τ simply by

$$(1.4) \quad \tau(\lambda) := \lambda \cap L \quad \text{for } \lambda \in \mathcal{FL}_{\beta_-}(\beta).$$

Clearly

$$(1.5) \quad \tau(\lambda) = \{i_-(a) + x \mid a \in \beta_-, x \in L_+ \text{ such that } i_+(x) + a \in \lambda\}.$$

To prove that $\text{range}(\tau) \subset \mathcal{FL}_{L_-}(L)$ and that τ is continuous, we introduce an alternative description of $\tau(\lambda)$ in terms of bounded operators associated to λ . For a given $\lambda \in \mathcal{FL}_{\beta_-}(\beta)$, we fix a direct sum decomposition

$$\lambda = (\lambda \cap \beta_-) \dot{+} \mu$$

with a suitable closed μ . Let $\pi_+ : \beta \rightarrow \beta_+$ denote the projection along β_- . Then to claim that (λ, β_-) is a Fredholm pair is equivalent to claiming that the projection $\pi_\lambda := \pi_+|_\lambda : \lambda \rightarrow \beta_+$ is a Fredholm operator. So we deduce that $F_\lambda := \pi_+(\lambda) = \pi_\lambda(\mu)$ is closed. For later use we notice that

$$(1.6) \quad \dim \beta_+ / F_\lambda = \dim(\beta_+ \dot{+} \beta_-) / (\lambda \dot{+} \beta_-) = \dim \lambda \cap \beta_- < +\infty.$$

By the injectivity of $\pi_+|_\mu$ we can write μ as the graph of a uniquely determined bounded operator

$$f_\mu : F_\lambda \longrightarrow \beta_-.$$

Then we rewrite

$$(1.7) \quad \tau(\lambda) = i_-(\lambda \cap \beta_-) + \text{graph}(\varphi_\lambda),$$

where

$$\begin{array}{ccc} \varphi_\lambda : i_+^{-1}(F_\lambda) & \longrightarrow & L_- \\ x & \mapsto & i_- \circ f_\mu \circ i_+(x) \end{array}$$

Since φ_λ is bounded and its domain is closed in L , its graph is also closed in L , and so is $\tau(\lambda)$ which differs from $\text{graph}(\varphi_\lambda)$ only by a space of finite dimension. But moreover:

LEMMA 1.2. *For each $\lambda \in \mathcal{FL}_{\beta_-}(\beta)$, we have $\tau(\lambda) \in \mathcal{FL}_{L_-}(L)$.*

PROOF. In the exact sequence

$$\begin{array}{ccccccc} 0 & \longrightarrow & F_\lambda & \hookrightarrow & \beta_+ & \xrightarrow{p} & \beta_+ / F_\lambda \longrightarrow 0 \\ & & & & \uparrow i_+ & & \\ & & & & L_+ & & \end{array}$$

the range of i_+ is dense in β_+ and $\dim \beta_+ / F_\lambda < +\infty$. So, the map $p \circ i_+$ is surjective. We therefore have

$$(1.8) \quad \beta_+ = F_\lambda + i_+(L_+)$$

and $\ker(p \circ i_+) = i_+^{-1}(F_\lambda)$. It follows that

$$(1.9) \quad L_+ / i_+^{-1}(F_\lambda) \cong (F_\lambda + i_+(L_+)) / F_\lambda = \beta_+ / F_\lambda.$$

This implies that the closed subspace $i_+^{-1}(F_\lambda)$ of L_+ is of finite codimension.

Now let $x, y \in i_+^{-1}(F_\lambda)$ and set $a := i_+(x)$ and $b := i_+(y)$. Then

$$\begin{aligned}\omega_L(x + \varphi_\lambda(x), y + \varphi_\lambda(y)) &= \omega_L(x, \varphi_\lambda(y)) + \omega_L(\varphi_\lambda(x), y) \\ &= \omega_\beta(a, f_\mu(b)) + \omega_\beta(f_\mu(a), b) \\ &= \omega_\beta(a + f_\mu(a), b + f_\mu(b)) = 0\end{aligned}$$

by the compatibility condition (1.3) and the isotropy of μ . So graph φ_λ is isotropic. Moreover, we have

$$\dim(\text{graph}(\varphi_\lambda)^0 / \text{graph}(\varphi_\lambda)) = 2 \dim(L_+ / i_+^{-1}(F_\lambda)) = 2 \dim(\beta_+ / F_\lambda).$$

Here $\text{graph}(\varphi_\lambda)^0$ denotes the annihilator of $\text{graph}(\varphi_\lambda)$ with respect to the symplectic form ω_L . Clearly,

$$i_-(\lambda \cap \beta_-) \subset \text{graph}(\varphi_\lambda)^0 \quad \text{and} \quad i_-(\lambda \cap \beta_-) \cap \text{graph}(\varphi_\lambda) = \{0\}.$$

Further, we have

$$\dim i_-(\lambda \cap \beta_-) = \dim(\lambda \cap \beta_-) = \dim(\beta_+ / F_\lambda),$$

since the Fredholm index of the Lagrangian pair (λ, β_-) vanishes. From this dimension examination we see that adding $i_-(\lambda \cap \beta_-)$ to $\text{graph}(\varphi_\lambda)$ makes $\tau(\lambda)$ a Lagrangian subspace of L . It also follows that $\tau(\lambda) \cap L_- = i_-(\lambda \cap \beta_-)$ is of finite dimension and that $L_- + \tau(\lambda) = L_- + \text{graph}(\varphi_\lambda)$ is of finite codimension, hence $(\tau(\lambda), L_-)$ is a Fredholm pair in L . $\square$

REMARK 1.3. From equation (1.7) it particularly follows that

$$\tau(\mathcal{M}_{\beta_-}(\beta)) \subset \mathcal{M}_{L_-}(L).$$

1.2. The continuity of τ . We fix a closed $W \subset L_-$ with $\dim L_- / W < +\infty$ and choose a Lagrangian subspace θ of β with $\theta \pitchfork \beta_+$ and $W_\beta \subset \theta \subset W_\beta^0$, where $W_\beta := i_-^{-1}(W)$. Here “ $\pitchfork$ ” means that the two subspaces intersect transversally. We notice that

$$W^0 = L_- \dot{+} (L_+ \cap W^0)$$

and, correspondingly,

$$W_\beta^0 = \beta_- \dot{+} (\beta_+ \cap W_\beta^0).$$

Next we exploit that the injection $i_- : \beta_- \rightarrow L_-$ has a dense range. Similar to the short exact sequence at the beginning of the proof of Lemma 1.2, we have

$$\begin{array}{ccccccc} 0 & \longrightarrow & W & \hookrightarrow & L_- & \xrightarrow{q} & L_- / W \longrightarrow 0 \\ & & & & \uparrow i_- & & \\ & & & & \beta_- & & \end{array}$$

We deduce, as above,

$$L_- = W + i_-(\beta_-) \quad \text{and} \quad \dim(\beta_- / W_\beta) = \dim(L_- / W).$$

Moreover, we have

$$(1.10) \quad i_+(W^0 \cap L_+) = W_\beta^0 \cap \beta_+.$$

To show the inclusion “ $\subset$ ”, we consider any $x \in W^0 \cap L_+$. Then $\omega_L(x, y) = 0$ for all $y \in W$, and hence also for $y = i_-(z)$ for any $z \in W_\beta = i_-^{-1}(W)$. Now, by (1.3),

$$0 = \omega_L(x, i_-(z)) = \omega_\beta(i_+(x), z).$$

So,

$$i_+(x) \in W_\beta^0 \cap \beta_+.$$

We deduce the identity “ $=$ ” by the following dimension examination:

$$2 \dim(W^0 \cap L_+) = \dim(W^0/W) = \dim(W_\beta^0/W_\beta) = 2 \dim(W_\beta^0 \cap \beta_+).$$

Equation (1.10) permits us to rewrite

$$W_\beta^0 = i_+(L_+ \cap W^0) \dot{+} \beta_-$$

and to define

$$\begin{aligned} i_W : W_\beta^0 &\longrightarrow W^0 \\ i_+(x) + z &\longmapsto x + i_-(z) \end{aligned}$$

for $x \in L_+ \cap W^0$ and $z \in \beta_-$. We obtain a new splitting of the symplectic Hilbert spaces:

PROPOSITION 1.4. *The space $\eta := i_W(\theta) + W$ is a Lagrangian subspace of L and the mapping $i_W|_\theta : \theta \rightarrow \eta$ has a dense image. Further, we have new direct sum decompositions*

$$\beta = \beta_+ \dot{+} \theta \quad \text{and} \quad L = L_+ \dot{+} \eta$$

which are compatible with regard to the symplectic forms ω_L and ω_β (similar to (1.3)).

PROOF. Clearly

$$W \subset \eta = i_W(\theta) + W \subset W^0 \quad \text{and} \quad \dim W^0/W < +\infty,$$

hence η is also closed and isotropic. We notice that the mapping $q \circ i_W|_\theta$ is surjective with $\ker q \circ i_W|_\theta = W_\beta$, where $q : \eta \rightarrow \eta/W$ denotes the projection. So,

$$W_\beta^0/W_\beta \supset \theta/W_\beta \cong \eta/W \subset W^0/W.$$

Then, from the dimension examination

$$\dim(W_\beta^0/W_\beta) = \dim(W^0/W),$$

it follows that η is a Lagrangian subspace of L .

To see that the range of $i_W|_\theta$ is dense in η we recall that the mapping $i_W : W_\beta^0 \rightarrow W^0$ is an isomorphism $W_\beta^0 \cap \beta_+ \cong W^0 \cap L_+$ on the first finite-dimensional component, and it is equal to the dense embedding $i_- : \beta_- \rightarrow L_-$ on the second component, hence its restriction to θ has a dense range in η .

The new direct sum decompositions and the compatibility of the symplectic forms follow at once. $\square$

The preceding proposition permits a further simplification of the graph representation of $\tau(\lambda)$, obtained in (1.7):

COROLLARY 1.5. *For any $\lambda \in \mathcal{FL}_{\beta_-}(\beta)$ with $\lambda \pitchfork \theta$, we have*

$$\tau(\lambda) = \text{graph}(i_W \circ f_\lambda \circ i_+),$$

where $f_\lambda : \beta_+ \rightarrow \theta$ such that $\text{graph } f_\lambda = \lambda$.

Now we can prove the continuity of τ and the invariance of the Maslov index under τ . We set

$$\mathcal{FL}_{W_\beta}(\beta)^{(0)} := \{\mu \in \mathcal{FL}_{W_\beta}(\beta) \mid \mu \cap W_\beta = \{0\}\}.$$

Then we have an open covering

$$\bigcup_W \mathcal{FL}_{W_\beta}(\beta)^{(0)} = \mathcal{FL}_{\beta_-}(\beta),$$

where the union is taken over all closed subspaces $W \subset L_-$ of finite codimension. It follows that $\tau(\mathcal{FL}_{W_\beta}(\beta)^{(0)}) \subset \mathcal{FL}_W(L)^{(0)}$. Thus, we have established restrictions

$$\tau_W : \mathcal{FL}_{W_\beta}(\beta)^{(0)} \longrightarrow \mathcal{FL}_W(L)^{(0)}$$

of τ for each W .

We fix a W . We denote the space of Lagrangian subspaces in a finite-dimensional symplectic space by $\text{Lag}(\cdot)$ and define the reduction map

$$\begin{aligned} \rho_{W_\beta} : \mathcal{FL}_{W_\beta}(\beta)^{(0)} &\longrightarrow \text{Lag}(W_\beta^0/W_\beta) \\ \lambda &\mapsto (\lambda \cap W_\beta^0 + W_\beta) / W_\beta \end{aligned}$$

Then, for each Lagrangian subspace θ in β with $\theta \supset W_\beta$ and $\theta \pitchfork \beta_+$ (as before), the set

$$U(W_\beta, \theta) := \{\Lambda \in \text{Lag}(W_\beta^0/W_\beta) \mid \Lambda \pitchfork \theta/W_\beta\}$$

is open in $\text{Lag}(W_\beta^0/W_\beta)$ and we have an open covering

$$\bigcup_{\theta \pitchfork \beta_+} \rho_{W_\beta}^{-1}(U(W_\beta, \theta)) = \mathcal{FL}_{W_\beta}(\beta)^{(0)}.$$

By Corollary 1.5, the mapping τ is continuous on each $\rho_{W_\beta}^{-1}(U(W_\beta, \theta))$, and so it is continuous on the whole $\mathcal{FL}_{\beta_-}(\beta)$. This concludes the proof of (a) of Theorem 1.1.

Moreover, we have

$$\tau(\rho_{W_\beta}^{-1}(U(W_\beta, \theta))) \subset \rho_W^{-1}(U(W, \tau_W(\theta))),$$

where the reduction map $\rho_W : \mathcal{FL}_W(L)^{(0)} \rightarrow \text{Lag}(W^0/W)$ is defined correspondingly to ρ_{W_β} . We denote by

$$\overline{\tau}_W : \text{Lag}(W_\beta^0/W_\beta) \longrightarrow \text{Lag}(W^0/W)$$

the mapping naturally induced by τ_W . Then we have the following finite-dimensional symplectic reduction:

PROPOSITION 1.6. *The diagram*

$$(1.11) \quad \begin{array}{ccccc} \mathcal{FL}_{\beta_-}(\beta) & \xleftarrow{\quad} & \mathcal{FL}_{W_\beta}(\beta)^{(0)} & \xrightarrow{\rho_{W_\beta}} & \text{Lag}(W_\beta^0/W_\beta) \\ \tau \downarrow & & \tau_W \downarrow & & \downarrow \cong \overline{\tau_W} \\ \mathcal{FL}_{L_-}(L) & \xleftarrow{\quad} & \mathcal{FL}_W(L)^{(0)} & \xrightarrow{\rho_W} & \text{Lag}(W^0/W) \end{array}$$

is commutative.

For any continuous curve $\{\lambda_t\}_{t \in [0,1]} \in \mathcal{FL}_{\beta_-}(\beta)$, we can find a closed subspace $W \subset L_-$ of finite codimension such that the whole curve is contained in $\mathcal{FL}_{W_\beta}(\beta)^{(0)}$, respectively $\{\tau(\lambda_t)\}_{t \in [0,1]}$ is contained in $\mathcal{FL}_W(L)^{(0)}$. By finite symplectic reduction we obtain at once:

COROLLARY 1.7. *The Maslov index coincides under the transformations τ , τ_W , and $\overline{\tau_W}$ for loops and also for paths.*

NOTE. For paths, the Maslov index depends on the choice of the Maslov cycle. In $\text{Lag}(W^0/W)$, the Maslov index is taken with respect to the Maslov cycle $\mathcal{M}_{L_-/W}(W^0/W)$. Correspondingly, the Maslov index in $\text{Lag}(W_\beta^0/W_\beta)$ is taken with respect to the Maslov cycle $\mathcal{M}_{\beta_-/W_\beta}(W_\beta^0/W_\beta)$. Note that the specified Maslov cycle in $\text{Lag}(W_\beta^0/W_\beta)$ is mapped onto the specified Maslov cycle in $\text{Lag}(W^0/W)$ by $\overline{\tau_W}$.

Proposition 1.6 and Corollary 1.7 together with Remark 1.3 give the proof of (b) and (c) of Theorem 1.1.

2. The General Spectral Flow Formula

Let $\mathcal{H}$ be a real separable Hilbert space and A an (unbounded) closed symmetric operator defined on the domain $D_{\min}$ which is supposed to be dense in $\mathcal{H}$. Let A^* denote its adjoint operator with domain $D_{\max}$. We have that $A^*|_{D_{\min}} = A$ and that A^* is the maximal closed extension of A in $\mathcal{H}$.

We form the space β of *natural boundary values* with the *natural trace map* γ in the following way:

$$\begin{array}{ccc} D_{\max} & \xrightarrow{\gamma} & D_{\max}/D_{\min} =: \beta \\ x & \mapsto & \gamma(x) = [x] := x + D_{\min} \end{array}$$

The space β becomes a symplectic Hilbert space with the scalar product induced by the graph norm

$$(2.1) \quad (x, y)_\beta := (x, y) + (Ax, Ay)$$

and the symplectic form given by Green's form

$$(2.2) \quad \omega([x], [y]) := (Ax, y) - (x, Ay) \quad \text{for } [x], [y] \in \beta.$$

We define the *natural Cauchy data space* $\Lambda := \gamma(\ker A^*)$. It is a Lagrangian subspace of β under the assumption that A admits at least one self-adjoint Fredholm extension A_D . Actually, we shall assume a little more, namely that

A has a self-adjoint extension A_D with compact resolvent. Then $(\Lambda, \gamma(D))$ is a Fredholm pair of subspaces of β , i.e. $\Lambda \in \mathcal{FL}_{\gamma(D)}(\beta)$.

We consider a continuous curve $\{C_t\}_{t \in [0,1]}$ in the space of bounded self-adjoint operators on $\mathcal{H}$ and assume that the operators $A^* + C_t - r$ have no 'inner solutions', i.e. satisfy the *weak unique continuation property* (UCP)

$$\ker(A^* + C_t - r) \cap D_{\min} = \{0\}$$

for $t \in [0, 1]$ and $|r| < \varepsilon_0$ with $\varepsilon_0 > 0$.

Clearly, the domains $D_{\max}$ and $D_{\min}$ are unchanged by the perturbation C_t for any t . So, β does not depend on the parameter t . Moreover, the symplectic form ω is invariantly defined on β and so also independent of t . It follows (see [2], Theorem 3.9) that the curve $\{\Lambda_t := \gamma(\ker(A^* + C_t))\}$ is continuous in $\mathcal{FL}_{\gamma(D)}(\beta)$.

Given this, the family $\{A_D + C_t\}$ can be considered at the same time in the spectral theory of self-adjoint operators, defining a spectral flow, and in the symplectic category, defining a Maslov index. Under the preceding assumptions, the main result obtainable at that level is the following general spectral flow formula (proved in [2], Theorem 5.1):

THEOREM 2.1. *Let A_D be a self-adjoint extension of A with compact resolvent and let $\{A_D + C_t\}$ be a family satisfying the UCP assumption. Then*

$$\text{sf}\{A_D + C_t\} = \text{mas}(\{\Lambda_t\}, \gamma(D)).$$

3. A Proof of the Yoshida–Nicolaescu Formula

Let M be a closed connected smooth Riemannian manifold and let $\Sigma \subset M$ be a hypersurface. Let

$$\{A_t := A_0 + C_t : C^\infty(M; S) \longrightarrow C^\infty(M; S)\}_{0 \leq t \leq 1}$$

be a continuous family of symmetric elliptic differential operators of first order with the same principal symbol, acting on sections of a real bundle S over M . The variation of the fixed operator A_0 is given by a continuous family $\{C_t\}_{t \in [0,1]}$ of smooth symmetric bundle homomorphisms. We assume that the normal bundle of the hypersurface Σ is orientable and that all metric structures of M and S are *product* in a collar neighbourhood $\mathcal{N} = (-1, 1) \times \Sigma$ of Σ . We have

$$(3.1) \quad A_t = \sigma \left(\frac{\partial}{\partial \tau} + B_t \right) \text{ on } \mathcal{N},$$

where τ denotes the normal coordinate, σ is orthogonal (assuming $\sigma^2 = -\text{Id}$), $\sigma B_t = -B_t \sigma$, and B_t is a self-adjoint elliptic differential operator over Σ , called the *tangential operator*. Here the point of the product structure is that then σ and B_t do not depend on the normal variable.

We cut the manifold at Σ and attach a copy of Σ to each side. So, we obtain a new manifold $M_\sharp$ with boundary $\Sigma_0 \sqcup \Sigma_1 = (-\Sigma) \sqcup \Sigma$. Then the β -space of

$M_{\sharp}$, being a $C^{\infty}(\partial M_{\sharp})$ -module, splits according to the connected components of $\partial M_{\sharp}$ and we obtain two symplectic Hilbert spaces

$$\beta := \beta_0 \dot{+} \beta_1 \quad \text{and} \quad L := L_0 \dot{+} L_1$$

with

$$\gamma = \gamma_0 \oplus \gamma_1 : D_{\max}(M_{\sharp}) \longrightarrow \beta_0 \dot{+} \beta_1$$

and $L_j = L^2(\pm\Sigma; S|_{\pm\Sigma})$ for $j = 0, 1$. We note that L_0 and L_1 are naturally identified as Hilbert spaces, but their symplectic forms have opposite signs. In β we have a Lagrangian subspace

$$(3.2) \quad \Delta_{\beta} := \{(x, x) \in \beta_0 \dot{+} \beta_1 \mid \gamma_0(s) = x = \gamma_1(s) \text{ for } s \in H^1(M)\},$$

where $H^1(M)$ denotes the first order Sobolev space. Since M is closed, the operator A_t on $H^1(M)$ is a self-adjoint Fredholm operator. It can be identified with the operator $A_{t,D}^{\sharp} = A_{0,D}^{\sharp} + C_t$ over the new manifold $M_{\sharp}$ with domain

$$D := \{s \in D_{\max}(M_{\sharp}) \mid \gamma_0(s) = \gamma_1(s)\},$$

i.e. it can be considered as a global self-adjoint boundary problem with $\gamma(D) = \Delta_{\beta}$. (Actually, D coincides with $H^1(M)$).

We set $\beta_- := \Delta_{\beta}$. In L , we have a Lagrangian subspace

$$(3.3) \quad L_- := \text{the diagonal of } L^2(-\Sigma; S|_{-\Sigma}) \dot{+} L^2(\Sigma; S|_{\Sigma}).$$

Clearly, the embedding $\beta_- \hookrightarrow L_-$ is bounded and dense.

To define suitable complementary Lagrangian subspaces β_+ and L_+ , we must fall back on a spectral resolution $\{\varphi_k, \lambda_k\}$ of $L^2(\Sigma)$ by eigensections of B_0 . (Here and in the following we do not mention the bundle S). For simplicity, we assume $\ker B_0 = \{0\}$. Otherwise we must decompose the finite-dimensional symplectic vector space $\ker B_0$ into two Lagrangian subspaces and add these spaces to the half parts defined by the spectral cut at 0.

Following [3], Proposition 7.15 (for related results see also [5] and [11]), we decompose

$$\beta_0 = \beta_-^0 \dot{+} \beta_+^0 \quad \text{and} \quad \beta_1 = \beta_-^1 \dot{+} \beta_+^1,$$

where

$$\beta_-^1 := \overline{[\{\varphi_k\}_{k<0}]}^{H^{\frac{1}{2}}(\Sigma)} \quad \text{and} \quad \beta_+^1 := \overline{[\{\varphi_k\}_{k>0}]}^{H^{-\frac{1}{2}}(\Sigma)}$$

and

$$\beta_-^0 := \overline{[\{\varphi_k\}_{k<0}]}^{H^{-\frac{1}{2}}(\Sigma)} \quad \text{and} \quad \beta_+^0 := \overline{[\{\varphi_k\}_{k>0}]}^{H^{\frac{1}{2}}(\Sigma)}.$$

In a similar way, we decompose

$$L_0 = L_-^0 \dot{+} L_+^0 \quad \text{and} \quad L_1 = L_-^1 \dot{+} L_+^1$$

with

$$L_-^1 := \overline{[\{\varphi_k\}_{k<0}]}^{L^2(\Sigma)} \quad \text{and} \quad L_+^1 := \overline{[\{\varphi_k\}_{k>0}]}^{L^2(\Sigma)}$$

and

$$L_-^0 := \overline{[\{\varphi_k\}_{k<0}]^{L^2(\Sigma)}} \quad \text{and} \quad L_+^0 := \overline{[\{\varphi_k\}_{k>0}]^{L^2(\Sigma)}}.$$

Rewriting

$$(3.4) \quad \beta = \beta_0 \dot{+} \beta_1 = \beta_-^0 \dot{+} \beta_+^0 \dot{+} \beta_-^1 \dot{+} \beta_+^1,$$

we obtain

$$\beta_- = \Delta_\beta = \{(a, b, a, b) \mid (a, b) = \gamma_0(s) = \gamma_1(s) \text{ with } s \in H^1(M)\}.$$

Correspondingly, we define

$$\beta_+ := \{(x, 0, 0, y) \mid x \in \beta_-^0, y \in \beta_+^1\}$$

and

$$L_+ := \{(u, 0, 0, v) \mid u \in L_-^0, v \in L_+^1\}.$$

Clearly, we have $L = L_- \dot{+} L_+$, a dense bounded embedding $L_+ \hookrightarrow \beta_+$, and $\Delta_\beta \cap \beta_+ = \{0\}$. From the decomposition (3.4) we have also that $\Delta_\beta \dot{+} \beta_+ = \beta$. Then, as explained above in Section 2, the β -theory gives the continuity of the family of Cauchy data spaces $\{\Lambda_t\}$ (of the continuous operator family $\{A_t\}$, considered over $M_\sharp$). They are all Lagrangian subspaces of β and make Fredholm pairs with $\beta_- = \Delta_\beta = \gamma(H^1(M))$. From the General Spectral Flow Formula (here Theorem 2.1) and by the criss-cross reduction of the Maslov index (Theorem 1.1), we obtain

$$(3.5) \quad \text{sf}\{A_0 + C_t\} = \text{sf}\{A_{0,D}^\sharp + C_t\}$$

$$(3.6) \quad \stackrel{\text{Th.2.1}}{=} \text{mas}(\{\Lambda_t\}, \Delta_\beta)$$

$$(3.7) \quad \stackrel{\text{Th.1.1}}{=} \text{mas}(\{\Lambda_t \cap L\}, L_-).$$

Note that here

$$\Lambda_t \cap L = \{s|_{(-\Sigma) \cup \Sigma} \mid s \in H^{\frac{1}{2}}(M_\sharp) \text{ and } A_t(s) = 0 \text{ in } M_\sharp \setminus \partial M_\sharp\},$$

i.e. it coincides with the 'conventional' L^2 -definition of the Cauchy data spaces.

In the particular case of a *partitioned* manifold

$$M = M_0 \cup_\Sigma M_1 \quad \text{with } \Sigma = \partial M_0 = \partial M_1 = M_0 \cap M_1,$$

not only β and L split but also the Cauchy data spaces split

$$\Lambda_t = \Lambda_t^0 \dot{+} \Lambda_t^1,$$

according to the splitting of M into two parts. So, we obtain from (3.7) the true Yoshida–Nicolaescu Formula, though without any assumptions about the regularity at the endpoints or the differentiability of the curve:

THEOREM 3.1.

$$\begin{aligned} \text{sf}\{A_0 + C_t\} &= \text{mas}(\{\Lambda_t^0 \cap L^2(-\Sigma) \dot{+} \Lambda_t^1 \cap L^2(\Sigma)\}, L_-) \\ &=: \text{mas}(\{\Lambda_t^0 \cap L^2(-\Sigma)\}, \{\Lambda_t^1 \cap L^2(\Sigma)\}), \end{aligned}$$

where the last expression is just a rewriting of the Maslov index of Fredholm pairs of two curves:

REMARK 3.2. (a) We notice that the subspaces β_- and L_- are defined independently of a reference tangential operator, here B_0 , but the choice of any other reference operator B_t would have given a different decomposition, though not a different result.

(b) We would like to emphasize that the Yoshida–Nicolaescu formulas in the literature always assume product structures near Σ , whereas the general spectral flow formulas, as proved in [2] and expressed in [3] in $\beta \subset H^{-1/2}(\Sigma)$, do not require product structures near Σ . However, we also need product structures near Σ , to apply our criss-cross reduction theorem and to transform the general spectral flow formulas, expressed in ‘natural’ distribution spaces, into ‘conventional’ L^2 -formulas. Possibly, the criss-cross reduction theorem may provide one explanation for the need of product structures for L^2 -formulas.

(c) We also want to point to a misprint in [3], p. 74 (after Equation (7.13)), where it must read that ‘ $\gamma(S) \cap L^2(\widehat{\Sigma})$ is not closed in $L^2(\widehat{\Sigma})$ ’ instead of ‘ $\gamma(S) \cap L^2(\Sigma)$ is not closed in $L^2(\Sigma)$ ’.

Appendix A. Addendum and Corrections to [2]

Let $\mathcal{L}$ denote the space of all Lagrangian subspaces of a real separable symplectic Hilbert space $\mathcal{H}$, and let $\mathcal{L}^{\mathbb{C}}$ denote the space of all complex Lagrangian subspaces of $\mathcal{H} \otimes \mathbb{C}$. As correctly observed in [2], the full group $\mathcal{U}(\mathcal{H})$ of unitary operators of $\mathcal{H}$ does *not* act on $\mathcal{FL}_{\lambda_0}(\mathcal{H})$, but the reduced group $\mathcal{U}_c(\mathcal{H})$ does. It consists of unitary operators of the form $\text{Id} + K$, where K is a compact operator. In [2], below on p. 5, we claimed that the reduced group acts transitively on $\mathcal{FL}_{\lambda_0}(\mathcal{H})$, i.e. the mapping

$$\begin{array}{ccc} \rho: & \mathcal{U}_c(\mathcal{H}) & \longrightarrow \mathcal{FL}_{\lambda_0}(\mathcal{H}) \\ & U & \mapsto U(\lambda_0^\perp) \end{array}$$

is surjective. This claim is erroneous, since the difference of the orthogonal projections onto a Fredholm pair of closed subspaces of $\mathcal{H}$ need not be of the form $\text{Id} + K$, but can become an arbitrary Fredholm operator as proved in [3], Appendix.

However, if we replace $\mathcal{U}_c(\mathcal{H})$ by $\mathcal{U}(\mathcal{H})$, $\mathcal{FL}_{\lambda_0}(\mathcal{H})$ by $\mathcal{L}$, $\mathcal{U}_c(\mathcal{H} \otimes \mathbb{C})$ by $\mathcal{U}(\mathcal{H} \otimes \mathbb{C})$, and $\mathcal{FL}_{\lambda_0 \otimes \mathbb{C}}^{\mathbb{C}}(\mathcal{H} \otimes \mathbb{C})$ by $\mathcal{L}^{\mathbb{C}}$, we have the same results as in [2], §§ 1.1–1.2:

The group $\mathcal{U}(\mathcal{H})$ (resp. $\mathcal{U}(\mathcal{H} \otimes \mathbb{C})$) acts transitively on $\mathcal{L}$ (resp. on $\mathcal{L}^{\mathbb{C}}$). So let

$$(A.1) \quad \begin{array}{ccc} \rho: & \mathcal{U}(\mathcal{H}) & \longrightarrow \mathcal{L} \\ & U & \mapsto U(\lambda_0^\perp) \end{array}$$

and

$$(A.2) \quad \begin{array}{ccc} \rho^{\mathbb{C}}: & \mathcal{U}(\mathcal{H} \otimes \mathbb{C}) & \longrightarrow \mathcal{L}^{\mathbb{C}} \\ & g & \mapsto g(\lambda_0^\perp \otimes \mathbb{C}) \end{array}$$

denote the mappings defined by these actions. We obtain a commutative diagram

$$(A.3) \quad \begin{array}{ccc} \mathcal{U}(\mathcal{H}) & \xrightarrow{\tilde{\tau}} & \mathcal{U}(\mathcal{H} \otimes \mathbb{C}) \\ \downarrow \rho & & \downarrow \rho^{\mathbb{C}} \\ \mathcal{L} & \xrightarrow{\tau} & \mathcal{L}^{\mathbb{C}}, \end{array}$$

where $\tilde{\tau}$ denotes the complexification $U \mapsto U \otimes \text{Id}$.

Correspondingly to [2], Proposition 1.3 we have

PROPOSITION A.1. *The mapping*

$$\rho^{\mathbb{C}} \circ \Phi : \mathcal{U}(\mathcal{H}) \longrightarrow \mathcal{L}^{\mathbb{C}}$$

is a homeomorphism, where Φ is defined in the same way as in [2], p. 7.

Now we must add the following lemma to [2], following Definition 1.4:

LEMMA A.2. *Let $\lambda \in \mathcal{L}$ and $\lambda = U(\lambda_0^\perp)$. Then we have that*

$$\lambda \in \mathcal{FL}_{\lambda_0}(\mathcal{H}) \iff U\bar{U}^{-1} + \text{Id} \text{ is a Fredholm operator.}$$

PROOF. By identifying $\mathcal{H} \cong \lambda_0 \otimes \mathbb{C} \cong \lambda_0 \oplus \sqrt{-1}\lambda_0$, we represent U as

$$U = X + \sqrt{-1}Y$$

with $X, Y : \lambda_0 \rightarrow \lambda_0$. Since

$$U\bar{U}^{-1} + \bar{U}\bar{U}^{-1} = (U + \bar{U})\bar{U}^{-1} = 2X\bar{U}^{-1},$$

we have that $U\bar{U}^{-1} + \text{Id}$ is a Fredholm operator, if and only if X is a Fredholm operator.

First we assume $\lambda \in \mathcal{FL}_{\lambda_0}(\mathcal{H})$. Then we know already by [2], Equation (1.1) that

$$(A.4) \quad \ker X = \lambda \cap \lambda_0,$$

and we have also

$$(A.5) \quad \lambda + \lambda_0 = \{-Y(x) + \sqrt{-1}X(x) + y \mid x, y \in \lambda_0\}.$$

So

$$(A.6) \quad \mathcal{H}/(\lambda + \lambda_0) \cong \lambda_0/\text{range}(X),$$

hence $\text{range}(X)$ is closed and of finite codimension in λ_0 .

Conversely, if X is a Fredholm operator, then also by (A.4), (A.5), and (A.6) we have $\lambda \in \mathcal{FL}_{\lambda_0}(\mathcal{H})$. $\square$

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