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Some results on a cross-section in the tensor bundle

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Abstract

The present paper is devoted to some results concerning with the complete lifts of an almost complex structure and a connection in a manifold to its $(0, q)$-tensor bundle along the corresponding cross-section.

Keywords: Almost complex structure, Almost analytic tensor, Complete lift, Connection, Tensor bundle.

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1. Introduction

The behaviour of the lifts of tensor fields and connections on a manifold to its different bundles along the corresponding cross-sections are studied by several authors. For the case tangent and cotangent bundles, see [13, 14, 15] and also tangent bundles of order 2 and order r, see [3, 11]. In [2], the first author and his collaborator studied the complete lift of an almost complex structure in a manifold on the so-called pure cross-section of its (p, q)-tensor bundle by means of the Tachibana operator (for diagonal lift to the (p, q)-tensor bundle see [1] and for the $(0, q)$-tensor bundle see [5]). Moreover they proved that if a manifold admits an almost complex structure, then so does on the pure cross-section of its (p, q)-tensor bundle provided that the almost complex structure is integrable. In [6], the authors give detailed description of geodesics of the (p, q)- tensor bundle with respect to the complete lift of an affine connection.

The purpose of the present paper is two-fold. Firstly, to show the complete lift of an almost complex structure in a manifold to its $(0, q)$-tensor bundle along the corresponding cross-section, when restricted to the cross-section determined by an almost analytic tensor field, is an almost complex structure. Finally, to study the behavior of the complete lift of a connection on the cross-section of the $(0, q)$-tensor bundle.

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Throughout this paper, all manifolds, tensor fields and connections are always assumed to be differentiable of class C^{∞}. Also, we denote by $\Im_q^p(M)$ the set of all tensor fields of type (p,q) on M, and by $\Im_q^p(T_q^0(M))$ the corresponding set on the $(0,q)$ -tensor bundle $T_q^0(M)$. The Einstein summation convention is used, the range of the indices i,j,s being always $\{1,2,...,n\}$.

2. Preliminaries

Let M be a differentiable manifold of class C^{∞} and finite dimension n. Then the set $T_q^0(M)=\cup_{P\in M}T_q^0(P)$, $q>0$, is the tensor bundle of type $(0,q)$ over M, where $\cup$ denotes the disjoint union of the tensor spaces $T_q^0(P)$ for all $P\in M$. For any point $\tilde{P}$ of $T_q^0(M)$ such that $\tilde{P}\in T_q^0(M)$, the surjective correspondence $\tilde{P}\to P$ determines the natural projection $\pi: T_q^0(M)\to M$. The projection π defines the natural differentiable manifold structure of $T_q^0(M)$, that is, $T_q^0(M)$ is a C^{∞}-manifold of dimension $n+n^q$. If x^j are local coordinates in a neighborhood U of $P\in M$, then a tensor t at P which is an element of $T_q^0(M)$ is expressible in the form $(x^j, t_{j_1...j_q})$, where $t_{j_1...j_q}$ are components of t with respect to natural base. We may consider $(x^j,t_{j_1...j_q})=(x^j,x^{\bar{j}})=x^J$, $j=1,...,n$, $\bar{j}=n+1,...,n+n^q$, $J=1,...,n+n^{p+q}$ as local coordinates in a neighborhood $\pi^{-1}(U)$.

Let $V=V^i\frac{\partial}{\partial x^i}$ and $A=A_{j_1...j_q}dx^{j_1}\otimes\cdots\otimes dx^{j_q}$ be the local expressions in U of a vector field V and a $(0,q)-$tensor field A on M, respectively. Then the vertical lift ${}^VA$ of A and the complete lift ${}^CV$ of V are given, with respect to the induced coordinates, by

$$(2.1)\qquad {}^VA=\begin{pmatrix} 0 \\ A_{j_1...j_q}\end{pmatrix}$$

and

$$(2.2)\qquad {}^CV=\begin{pmatrix} V^j \\ -\sum\limits_{\lambda=1}^{q} t_{j_1...m...j_q}\partial_{j_\lambda}V^m\end{pmatrix}.$$

Suppose that there is given a tensor field $\xi\in\Im_q^0(M)$. Then the correspondence $x\mapsto\xi_x$, ξ_x being the value of ξ at $x\in M$, determines a mapping $\sigma_\xi: M\mapsto T_q^0(M)$, such that $\pi\circ\sigma_\xi=id_M$, and the n dimensional submanifold $\sigma_\xi(M)$ of $T_q^0(M)$ is called the cross-section determined by ξ. If the tensor field ξ has the local components $\xi_{k_1\cdots k_q}(x^k)$, the cross-section $\sigma_\xi(M)$ is locally expressed by

$$(2.3)\qquad \begin{cases} x^k=x^k, \\ x^{\bar{k}}=\xi_{k_1\cdots k_q}(x^k)\end{cases}$$

with respect to the coordinates $(x^k,x^{\bar{k}})$ in $T_q^0(M)$. Differentiating (2.3) by x^j, we see that n tangent vector fields B_j to $\sigma_\xi(M)$ have components

$$(2.4)\qquad (B_j^K)=(\frac{\partial x^K}{\partial x^j})=\begin{pmatrix}\delta_j^k \\ \partial_j\xi_{k_1\cdots k_q}\end{pmatrix}$$

with respect to the natural frame $\{\partial_k,\partial_{\bar{k}}\}$ in $T_q^0(M)$.

On the other hand, the fibre is locally expressed by

$$\begin{cases} x^k = const., \\ t_{k_1\cdots k_q} = t_{k_1\cdots k_q}, \end{cases}$$

$t_{k_1\cdots k_q}$ being considered as parameters. Thus, on differentiating with respect to $x^{\overline{j}} = t_{j_1\cdots j_q}$, we see that n^q tangent vector fields $C_{\overline{j}}$ to the fibre have components

$$(2.5)\qquad (C^K_{\overline{j}}) = (\frac{\partial x^K}{\partial x^{\overline{j}}}) = \begin{pmatrix} 0 \\ \delta^{j_1}_{k_1}\cdots\delta^{j_q}_{k_q} \end{pmatrix}$$

with respect to the natural frame $\{\partial_k, \partial_{\overline{k}}\}$ in $T^0_q(M)$.

We consider in $\pi^{-1}(U) \subset T^0_q(M)$, $n + n^q$ local vector fields B_j and $C_{\overline{j}}$ along $\sigma_\xi(M)$. They form a local family of frames $\left[B_j, C_{\overline{j}}\right]$ along $\sigma_\xi(M)$, which is called the adapted $(B, C)-$frame of $\sigma_\xi(M)$ in $\pi^{-1}(U)$. Taking account of (2.2) on the cross-section $\sigma_\xi(M)$, and also (2.4) and (2.5), we can easily prove that, the complete lift ${}^CV$ has along $\sigma_\xi(M)$ components of the form

$$(2.6)\qquad {}^CV = \begin{pmatrix} V^j \\ -L_V\xi_{j_1\cdots j_q} \end{pmatrix}$$

with respect to the adapted (B, C)-frame. From (2.1), (2.4) and (2.5), the vertical lift ${}^VA$ also has components of the form

$$(2.7)\qquad {}^VA = \begin{pmatrix} 0 \\ A_{j_1\ldots j_q} \end{pmatrix}$$

with respect to the adapted (B, C)- frame.

3. Almost complex structures on a pure cross-section in the $(0, q)$-tensor bundle

A tensor field $\xi \in \Im^0_q(M)$ is called pure with respect to $\varphi \in \Im^1_1(M)$, if [2, 4, 5, 7, 8, 9, 10, 12]:

$$(3.1)\qquad \varphi^r_{j_1}\xi_{r\cdots j_q} = \cdots = \varphi^r_{j_q}\xi_{j_1\cdots r} = \overset{*}{\xi}_{j_1\cdots j_q}.$$

In particular, vector and covector fields will be considered to be pure.

Let $\overset{*}{\Im}{}^0_q(M)$ denotes a module of all the tensor fields $\xi \in \Im^0_q(M)$ which are pure with respect to φ. Now, we consider a pure cross-section $\sigma^\varphi_\xi(M)$ determined by $\xi \in \overset{*}{\Im}{}^0_q(M)$. The complete lift ${}^C\varphi$ of φ along the pure cross-section $\sigma^\varphi_\xi(M)$ to $T^0_q(M)$ has local components of the form

$${}^C\varphi = \begin{pmatrix} \varphi^k_l & 0 \\ -(\Phi_\varphi\xi)_{lk_1\ldots k_q} & \varphi^{r_1}_{k_1}\delta^{r_2}_{k_2}\ldots\delta^{r_q}_{k_q} \end{pmatrix}$$

with respect to the adapted $(B, C)-$frame of $\sigma^\varphi_\xi(M)$, where $(\Phi_\varphi\xi)_{lk_1\cdots k_q} = \varphi^m_l\partial_m\xi_{k_1\cdots k_q} - \partial_l\overset{*}{\xi}_{k_1\cdots k_q} + \sum\limits_{a=1}^{q}(\partial_{k_a}\varphi^m_l)\xi_{k_1\cdots m\cdots k_q}$ is the Tachibana operator.

We consider that the local vector fields

$$ {}^{C}X_{(i)} = {}^{C}(\frac{\partial}{\partial x^i}) = {}^{C}(\delta_i^h \frac{\partial}{\partial x^h}) = \begin{pmatrix} \delta_i^h \\ 0 \end{pmatrix} $$

and

$$ {}^{V}X^{(\bar{i})} = {}^{V}(dx^{i_1} \otimes \cdots \otimes dx^{i_q}) = {}^{V}(\delta_{h_1}^{i_1} \cdots \delta_{h_q}^{i_q} dx^{h_1} \otimes \cdots \otimes dx^{h_q}) = \begin{pmatrix} 0 \\ \delta_{h_1}^{i_1} \cdots \delta_{h_q}^{i_q} \end{pmatrix} $$

$i = 1, ..., n, \bar{i} = n+1, ..., n+n^q$ span the module of vector fields in $\pi^{-1}(U)$. Hence, any tensor fields is determined in $\pi^{-1}(U)$ by their actions on ${}^{C}V$ and ${}^{V}A$ for any $V \in \Im_0^1(M)$ and $A \in \Im_q^0(M)$. The complete lift ${}^{C}\varphi$ along the pure cross-section $\sigma_\xi^\varphi(M)$ has the properties

$$ (3.2) \quad \begin{cases} {}^{C}\varphi({}^{C}V) = {}^{C}(\varphi(V)) + {}^{V}((L_V\varphi) \circ \xi), \forall V \in \Im_0^1(M), (i) \\ {}^{C}\varphi({}^{V}A) = {}^{V}(\varphi(A)), \forall A \in \Im_q^0(M), \quad (ii) \end{cases} $$

which characterize ${}^{C}\varphi$, where $\varphi(A) \in \Im_q^0(M)$. Remark that ${}^{V}((L_V\varphi) \circ \xi)$ is a vector field on $T_q^0(M)$ and locally expressed by

$$ {}^{V}((L_V\varphi) \circ \xi) = \begin{pmatrix} 0 \\ (L_V\varphi)_{i_1}^{j} \xi_{j i_2 \cdots i_q} \end{pmatrix} $$

with respect to the adapted (B, C)-frame, where $\xi_{i_1 \cdots i_q}$ are local components of ξ in M [5].

3.1. Theorem. *Let M be an almost complex manifold with an almost complex structure φ. Then, the complete lift ${}^{C}\varphi \in \Im_1^1(T_q^0(M))$, when restricted to the pure cross-section determined by an almost analytic tensor ξ on M, is an almost complex structure.*

Proof. If $V \in \Im_0^1(M)$ and $A \in \Im_q^0(M)$, in view of the equations (i) and (ii) of (3.2), we have

$$ (3.3) \quad ({}^{C}\varphi)^2({}^{C}V) = {}^{C}(\varphi^2)({}^{C}V) + {}^{V}(N_\varphi \circ \xi)({}^{C}V) $$

and

$$ (3.4) \quad ({}^{C}\varphi)^2({}^{V}A) = {}^{C}(\varphi^2)({}^{V}A), $$

where $N_{\varphi,X}(Y) = (L_{\varphi X}\varphi - \varphi(L_X\varphi))(Y) = [\varphi X, \varphi Y] - \varphi[X, \varphi Y] - \varphi[\varphi X, Y] + \varphi^2[X, Y] = N_\varphi(X, Y)$ is nothing but the Nijenhuis tensor constructed by φ.

Let $\varphi \in \Im_1^1(M)$ be an almost complex structure and $\xi \in \Im_q^0(M)$ be a pure tensor with respect to φ. If $(\Phi_\varphi \xi) = 0$, the pure tensor ξ is called an almost analytic $(0, q)-$tensor. In [4, 7, 9], it is proved that $\xi \circ \varphi \in \Im_q^0(M)$ is an almost analytic tensor if and only if $\xi \in \Im_q^0(M)$ is an almost analytic tensor. Moreover if $\xi \in \Im_q^0(M)$ is an almost analytic tensor, then $N_\varphi \circ \xi = 0$. When restricted to the pure cross-section determined by an almost analytic tensor ξ on M, from (3.3), (3.4) and linearity of the complete lift, we have

$$ ({}^{C}\varphi)^2 = {}^{C}(\varphi^2) = {}^{C}(-I_M) = -I_{T_q^0(M)}. $$

This completes the proof. $\square$

4. Complete lift of a symmetric affine connection on a cross-section in the $(0, q)$-tensor bundle

We now assume that ∇ is an affine connection (with zero torsion) on M. Let Γ^h_{ij} be components of ∇. The complete lift ${}^C\nabla$ of ∇ to $T^0_q(M)$ has components ${}^C\Gamma^I_{MS}$ such that

$$
\begin{aligned}
(4.1)\quad {}^C\Gamma^i_{ms} &= \Gamma^i_{ms},\ {}^C\Gamma^i_{\overline{m}s} ={}^C \Gamma^i_{m\overline{s}} ={}^C \Gamma^i_{\overline{m}\overline{s}} ={}^C \Gamma^{\overline{i}}_{\overline{m}\overline{s}} = 0, \\
{}^C\Gamma^{\overline{i}}_{m\overline{s}} &= -\sum_{c=1}^{q} \Gamma^{s_c}_{mi_c}\delta^{s_1}_{i_1}...\delta^{s_{c-1}}_{i_{c-1}}\delta^{s_{c+1}}_{i_{c+1}}...\delta^{s_q}_{i_q}, \\
{}^C\Gamma^{\overline{i}}_{\overline{m}s} &= -\sum_{c=1}^{q} \Gamma^{m_c}_{si_c}\delta^{m_1}_{i_1}...\delta^{m_{c-1}}_{i_{c-1}}\delta^{m_{c+1}}_{i_{c+1}}...\delta^{m_q}_{i_q}, \\
{}^C\Gamma^{\overline{i}}_{ms} &= \sum_{c=1}^{q}(-\partial_m\Gamma^a_{si_c} + \Gamma^r_{mi_c}\Gamma^a_{sr} + \Gamma^r_{ms}\Gamma^a_{ri_c})t_{i_1...i_{c-1}ai_{c+1}...i_q} \\
&\quad + \frac{1}{2}\sum_{b=1}^{q}\sum_{c=1}^{q}(\Gamma^l_{mi_c}\Gamma^r_{si_b} + \Gamma^l_{mi_b}\Gamma^r_{si_c})t_{i_1...i_{b-1}ri_{b+1}...i_{c-1}li_{c+1}...i_q} \\
&\quad + \sum_{d=1}^{q} t_{i_1...l...i_q} R_{i_dkm}{}^l
\end{aligned}
$$

with respect to the natural frame in $T^0_q(M)$, where δ^i_j-Kronecker delta and $R_{ikm}{}^l$ is components of the curvature tensor R of ∇ [6].

We now study the affine connection induced from ${}^C\nabla$ on the cross-section $\sigma_\xi(M)$ determined by the $(0, q)-$tensor field ξ in M with respect to the adapted (B, C)-frame of $\sigma_\xi(M)$. The vector fields $C_{\overline{j}}$ given by (2.5) are linearly independent and not tangent to $\sigma_\xi(M)$. We take the vector fields $C_{\overline{j}}$ as normals to the cross-section $\sigma_\xi(M)$ and define an affine connection $\widetilde{\nabla}$ induced on the cross-section. The affine connection $\widetilde{\nabla}$ induced $\sigma_\xi(M)$ from the complete lift ${}^C\nabla$ of a symmetric affine connection ∇ in M has components of the form

$$(4.2)\qquad \widetilde{\Gamma}^h_{ji} = (\partial_j B_i{}^A +{}^C \Gamma^A_{CB} B_j{}^C B_i{}^B)B^h{}_A,$$

where $B^h{}_A$ are defined by

$$(B^h{}_A, C^h{}_A) = (B_i{}^A, C_i{}^A)^{-1}$$

and thus

$$(4.3)\qquad B^h{}_A = (\delta^h_i, 0),\quad C^h{}_A = (-\partial_j\xi_{k_1...k_q}, \delta^{j_1}_{k_1}...\delta^{j_q}_{k_q}).$$

Substituting (4.1), (2.4), (2.5) and (4.3) in (4.2), we get

$$\widetilde{\Gamma}^h_{ji} = \Gamma^h_{ji},$$

where Γ^h_{ji} are components of ∇ in M.

From (4.2), we see that the quantity

$$(4.4)\qquad \partial_j B_i{}^A +{}^C \Gamma^A_{CB} B_j{}^C B_i{}^B - \Gamma^h_{ji} B_h{}^A$$

is a linear combination of the vectors $C_{\bar{i}}{}^{A}$. To find the coefficients, we put $A = \overline{h}$ in (4.4) and find

$$\nabla_j \nabla_i \xi_{h_1 \ldots h_q} + \sum_{\lambda=1}^{q} \xi_{h_1 \ldots l \ldots h_q} R_{h_\lambda ij}{}^{l}.$$

Hence, representing (4.4) by $\widetilde{\nabla}_j B_i{}^{A}$, we obtain

$$\widetilde{\nabla}_j B_i{}^{A} = (\nabla_j \nabla_i \xi_{h_1 \ldots h_q} + \sum_{\lambda=1}^{q} \xi_{h_1 \ldots l \ldots h_q} R_{h_\lambda ij}{}^{l}) C_{\overline{h}}{}^{A}. \tag{4.5}$$

The last equation is nothing but the equation of Gauss for the cross-section $\sigma_\xi(M)$ determined by $\xi_{h_1 \ldots h_q}$. Hence, we have the following proposition.

4.1. Proposition. *The cross-section $\sigma_\xi(M)$ in $T_q^0(M)$ determined by a $(0,q)$ tensor ξ in M with symmetric affine connection ∇ is totally geodesic if and only if ξ satisfies*

$$\nabla_j \nabla_i \xi_{h_1 \ldots h_q} + \sum_{\lambda=1}^{q} \xi_{h_1 \ldots l \ldots h_q} R_{h_\lambda ij}{}^{l} = 0.$$

Now, let us apply the operator $\widetilde{\nabla}_k$ to (4.5), we have

$$\widetilde{\nabla}_k \widetilde{\nabla}_j B_i{}^{A} = \nabla_k (\nabla_j \nabla_i \xi_{h_1 \ldots h_q} + \sum_{\lambda=1}^{q} \xi_{h_1 \ldots l \ldots h_q} R_{h_\lambda ij}{}^{l}) C_{\overline{h}}{}^{A}. \tag{4.6}$$

Recalling that

$$\widetilde{\nabla}_k \widetilde{\nabla}_j B_i{}^{A} - \widetilde{\nabla}_j \widetilde{\nabla}_k B_i{}^{A} = \widetilde{R}_{DCB}{}^{A} B_k{}^{D} B_j{}^{C} B_i{}^{B} - R_{kji}{}^{h} B_h{}^{A},$$

and using the Ricci identity for a tensor field of type $(0,q)$, from (4.6) we get

$$\begin{aligned} & \widetilde{R}_{DCB}{}^{A} B_k{}^{D} B_j{}^{C} B_i{}^{B} - R_{kji}{}^{h} B_h{}^{A} \\ = \ & [\sum_{\lambda=1}^{q} (\nabla_k R_{h_\lambda ij}{}^{l} - \nabla_j R_{h_\lambda ik}{}^{l}) \xi_{h_1 \ldots l \ldots h_q} - R_{kji}{}^{l} \nabla_l \xi_{h_1 \ldots h_q} \\ & - \sum_{\lambda=1}^{q} R_{kjh_\lambda}{}^{l} \nabla_i \xi_{h_1 \ldots l \ldots h_q} + \sum_{\lambda=1}^{q} R_{h_\lambda ij}{}^{l} \nabla_k \xi_{h_1 \ldots l \ldots h_q} - \sum_{\lambda=1}^{q} R_{h_\lambda ik}{}^{l} \nabla_j \xi_{h_1 \ldots l \ldots h_q}] C_{\overline{h}}{}^{A}. \end{aligned}$$

Thus we have the result below.

4.2. Proposition. $\widetilde{R}_{DCB}{}^{A} B_k{}^{D} B_j{}^{C} B_i{}^{B}$ *is tangent to the cross-section $\sigma_\xi(M)$ if and only if*

$$\begin{aligned} & \sum_{\lambda=1}^{q} (\nabla_k R_{h_\lambda ij}{}^{l} - \nabla_j R_{h_\lambda ik}{}^{l}) \xi_{h_1 \ldots l \ldots h_q} \\ = \ & R_{kji}{}^{l} \nabla_l \xi_{h_1 \ldots h_q} + \sum_{\lambda=1}^{q} R_{kjh_\lambda}{}^{l} \nabla_i \xi_{h_1 \ldots l \ldots h_q} - \sum_{\lambda=1}^{q} R_{h_\lambda ij}{}^{l} \nabla_k \xi_{h_1 \ldots l \ldots h_q} \\ & + \sum_{\lambda=1}^{q} R_{h_\lambda ik}{}^{l} \nabla_j \xi_{h_1 \ldots l \ldots h_q}. \end{aligned}$$

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