ABOUT GENERAL CONFORMAL ALMOST SYMPLECTIC
N-LINEAR CONNECTIONS ON K-COTANGENT BUNDLE

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DOI: 10.19062/1842-9238.2016.14.2.14

Abstract: In the present paper starting from the notions of: almost symplectic structure and
conformal almost symplectic structure, we define on k-cotangent bundle the notions of: conformal
almost symplectic N-linear connection and general conformal almost symplectic N-linear
connection. We determine the set of all general conformal almost symplectic N-linear connections
in the case when the nonlinear connection is arbitrary and we find important particular cases.

Keywords: k-cotangent bundle, almost symplectic structure, conformal almost symplectic
structure, conformal almost symplectic N-linear connection, general conformal almost symplectic
N-linear connection.

1. INTRODUCTION

The notion of Hamilton space was introduced by R. Miron in [6]–[8]. The Hamilton
spaces appear as dual via Legendre transformation, of the Lagrange spaces.

The differential geometry of the second order cotangent bundle was introduced and studied by R. Miron in [12], R. Miron, D. Hrimiuc, H. Shimada, V.S. Sabău in [11], Gh. Atanasiu and M. Târnoveanu in [1], etc.

The differential geometry of the k-cotangent bundle was introduced and studied by R. Miron [10], [12].

In the present section we keep the general setting from R. Miron [12], and subsequently we recall only some needed notions. For more details see [12].

Let M be a real n-dimensional C∞-manifold and let \( (T^k M, \pi^k, M) \),
\( (k \geq 2, k \in \mathbb{N}) \) be the k-cotangent bundle, where the total space is:

\[
T^k M = T^{k-1} M \times T^* M.
\] (1)

Let \( (x^i, y^{(i)}_1, \ldots, y^{(i)}_{k-1}, p_i) (i = 1, 2, \ldots, n) \) be the local coordinates of a point
\( u = (x, y^{(1)}_1, \ldots, y^{(k-1)}_1, p) \in T^k M \) in a local chart on \( T^* M \).

We denote by:

\[
\tilde{T}^k M = T^k M - \{0\} \quad \text{where } 0 : M \to T^k M \text{ is the null section of the projection } \pi^k.
\]

A change of local coordinates on the manifold \( T^k M \) is given by:
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\[
\begin{aligned}
\tilde{x}^i &= \tilde{x}^i(x^1, ..., x^n), \\
\tilde{y}^{(l)}(x) &= \frac{\partial \tilde{x}^i}{\partial x^i} y^{(l)}(x), \\
\tilde{y}^{(k-l)}(x) &= \frac{\partial \tilde{x}^i}{\partial x^i} y^{(k-l)}(x), \\
(k-1)\tilde{y}^{(k-l)}(x) &= \frac{\partial \tilde{y}^{(k-l)}(x)}{\partial x^i} y^{(k-l)}(x), \\
\bar{p}_j &= \frac{\partial x^i}{\partial x^j} p_j,
\end{aligned}
\]

We denote with \( N \) a nonlinear connection on the manifold \( T^{*k}M, (k \geq 2, k \in N) \), with the coefficients:

\[
\begin{aligned}
\left( N_{(k-1)}^{(l)} \right) (x, y^{(l)}, y^{(k-l)}, p, ..., y^{(k-l)}, p) &= \left( x, y^{(l)}, y^{(k-l)}, p, ..., y^{(k-l)}, p \right), \\
N_{(k-l)}^{(l)} (x, y^{(l)}, y^{(k-l)}, p) &= N_{(k-l)}^{(l)} ((i, j = 1, 2, ..., n)).
\end{aligned}
\]

The tangent space of \( T^{*k}M \) in the point \( u \in T^{*k}M \) is given by the direct sum of vector spaces:

\[
T_u (T^{*k}M) = N_{0, u} \oplus N_{1, u} \oplus ... \oplus N_{k-2, u} \oplus V_{k-1, u} \oplus W_{k, u}, \forall u \in T^{*k}M
\]

A local adapted basis to the direct decomposition (4) is given by:

\[
\left\{ \frac{\partial}{\partial x^i}, \frac{\partial}{\partial y^{(l)}}, ..., \frac{\partial}{\partial y^{(k-l)}}, \frac{\partial}{\partial p_j} \right\}, (i = 1, 2, ..., n),
\]

where:

\[
\begin{aligned}
\frac{\partial}{\partial x^i} &= \frac{\partial}{\partial x^i} - N_{(l)}^{(l)} \frac{\partial}{\partial y^{(l)}} - ... - N_{(k-l)}^{(l)} \frac{\partial}{\partial y^{(k-l)}} + N_{(k-l)}^{(l)} \frac{\partial}{\partial p_j}, \\
\frac{\partial}{\partial y^{(l)}} &= \frac{\partial}{\partial y^{(l)}} - N_{(l)}^{(l)} \frac{\partial}{\partial y^{(l)}} - ... - N_{(k-l)}^{(l)} \frac{\partial}{\partial y^{(k-l)}} + N_{(k-l)}^{(l)} \frac{\partial}{\partial p_j}, \\
\frac{\partial}{\partial y^{(k-l)}} &= \frac{\partial}{\partial y^{(k-l)}}, \\
\frac{\partial}{\partial p_j} &= \frac{\partial}{\partial p_j}
\end{aligned}
\]

and its dual basis \( \{ \partial x^i, \partial y^{(l)}(x), \partial y^{(k-l)}(x), \partial p_j \} \) determined by \( N \) and by the distribution \( W_k \).
2. CONFORMAL ALMOST SYMPLECTIC STRUCTURE

Let $D$ be an $N$-linear connection on $T^s k M$, with the local coefficients in the adapted basis $(\alpha)$:

$$D\Gamma(N) = \left\{ H^i_{\gamma jk}, C^i_{\alpha jh}, C_i^{jh} \right\}, (\alpha = 1, \ldots, k-1). \quad (7)$$

$D$ determines the $h-$, $w_1-$, $w_2-$,...,$w_k-$ covariant derivatives in the tensor algebra of d-tensor fields.

We consider on $\tilde{T}^s k M$, $(k \geq 2, k \in N)$, an almost symplectic structure $A$ given only by a nonsingular and skewsymmetric d-tensor field $a_{ij}$, of the type $(0, 2)$ :

$$A(x^i, y^{(1)}i, \ldots, y^{(k-1)}i, p_i) = \frac{1}{2} a_{ij} (x^i, y^{(1)}i, \ldots, y^{(k-1)}i, p_i) dx^j \wedge dx^i +$$
$$+ a_{ij} (x^i, y^{(1)}i, \ldots, y^{(k-1)}i, p_i) dy^{(1)}j \wedge dy^{(1)}j + \frac{1}{2} a_{ij} (x^i, y^{(1)}i, \ldots, y^{(k-1)}i, p_i) \delta p_i \wedge \delta p_j, \quad (i, j = 1, 2, \ldots, n) \quad (8)$$

The contravariant tensor field $a^{ij}$ is obtained from the equations:

$$a_{ij} a^{jk} = \delta^k_i \quad \text{Definition 1}$$

An N-linear connection $D$ is called almost symplectic if:

$$a_{ij}^{(a)} = 0, a_{ij}^{(b)} = 0, a_{ij}^h = 0, (\alpha = 1, \ldots, k-1). \quad (9)$$

We associate to the lift $A$ the operators of Obata's type given by:

$$\Omega_{hk}^{ij} = \frac{1}{2} (\delta_h^i \delta_k^j - a_{hk} a^{ij}), \quad \Omega_{hk}^{ij} = \frac{1}{2} (\delta_h^i \delta_k^j + a_{hk} a^{ij}). \quad (10)$$

Let $A_2 (\tilde{T}^s k M)$ be the set of all skewsymmetric d-tensor fields, of the type $(0,2)$ on $\tilde{T}^s k M, k \geq 2, k \in N$. As is easily shown, the relations for $a_{ij}, b_{ij} \in A_2 (\tilde{T}^s k M)$ defined by:

$$(a_{ij} \approx b_{ij}) \Leftrightarrow (\exists \lambda) \lambda(x, y^{(1)}, \ldots, y^{(k-1)}, p) \in F(\tilde{T}^s k M),$$
$$a_{ij} (x, y^{(1)}, \ldots, y^{(k-1)}, p) = e^{2\lambda(x, y^{(1)}, \ldots, y^{(k-1)}, p)} b_{ij} (x, y^{(1)}, \ldots, y^{(k-1)}, p)) \quad (11)$$

is an equivalence relation on $A_2 (\tilde{T}^s k M)$.

$\textbf{Definition 2}$ The equivalent class $\hat{A}$ of $A_2 (\tilde{T}^s k M)/ \approx$ to which $A$ belongs, is called conformal almost symplectic structure on $T^s k M$.

Thus:

$$\hat{A} = \{ A' \mid a_{ij}' (x, y^{(1)}, \ldots, y^{(k-1)}, p) = e^{2\lambda(x, y^{(1)}, \ldots, y^{(k-1)}, p)} a_{ij} (x, y^{(1)}, \ldots, y^{(k-1)}, p),$$
$$\lambda(x, y^{(1)}, \ldots, y^{(k-1)}, p) \in F(\tilde{T}^s k M) \}. \quad (12)$$

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3. GENERAL CONFORMAL ALMOST SYMPLECTIC N-LINEAR CONNECTIONS

**Definition 3** An N-linear connection, D, with local coefficients: \( D\Gamma(N) = \left( H^i_{jkh}, C^i_{(\alpha) jkh}, C^j_{(\alpha) i} \right) \), \((\alpha = 1,\ldots,k-1)\), is called general conformal almost symplectic N-linear connection with respect to \( \hat{A} \) if:

\[
a_{ijh} = K_{ijh}, \quad a_g^{(\alpha)} |_h = Q_{(\alpha)ijh}, \quad a_g^{(\alpha)} |^h = \hat{Q}_{(\alpha)ijh},
\]

where \( a_{ijh} \) and \( a_g^{(\alpha)} |_h \) denote the \( h \)-, \( v_\alpha \) - and \( w_k \) - covariant derivatives with respect to D and \( K_{ijh}, Q_{(\alpha)ijh}, \hat{Q}_{(\alpha)ijh} \) are arbitrary tensor fields on \( T^k M \) of the types (0,3), (0,3) and (2,1) respectively, with the properties:

\[
K_{ijh} = K_{ijh}, \quad Q_{(\alpha)ijh} = Q_{(\alpha)ijh}, \quad \hat{Q}_{(\alpha)ijh} = \hat{Q}_{(\alpha)ijh}, \quad (\alpha = 1,\ldots,k-1).
\]

**Definition 4** An N-linear connection, D, with local coefficients: \( D\Gamma(N) = \left( H^i_{jkh}, C^i_{(\alpha) jkh}, C^j_{(\alpha) i} \right) \), \((\alpha = 1,\ldots,k-1)\), for which there exists the 1-form \( \omega \),

\[
\omega = \omega_i dx^i + \hat{\omega}_i \delta^{(1)}_i + \ldots + \hat{\omega}_i \delta^{(k-1)}_i + \bar{\omega} \bar{\delta}_1,
\]

such that:

\[
\begin{cases}
a_{ijh} = 2\omega_h g_{ij}, & a_g^{(\alpha)} |_h = \hat{\omega}_h a_g^{(\alpha)}, \\
a_{ij} |^h = 2\bar{\omega}^h a_g,
\end{cases}
\]

where \( a_{ijh} \) and \( a_g^{(\alpha)} |_h \) denote the \( h \)-, \( v_\alpha \) - and \( w_k \) - covariant derivatives with respect to D, \((\alpha = 1,\ldots,k-1)\) is called conformal almost symplectic N-linear connection, with respect to the conformal almost symplectic d-structure \( \hat{A} \), corresponding to the 1-form \( \omega \) and it is denoted by: \( DT(N,\omega) \).

We shall determine the set of all general conformal almost symplectic N-linear connections, with respect to \( \hat{A} \).

Let \( D\Gamma(N) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & H^i_{jkh}, C^i_{(\alpha) jkh}, C^j_{(\alpha) i} \end{pmatrix} \) \((\alpha = 1,\ldots,k-1)\) be the local coefficients of a fixed N-linear connection \( D \), where \( (N^i_i, (x, y^{(1)}_1, \ldots, y^{(k-1)}_1, p), \cdots, N^i_i, (x, y^{(1)}_n, \ldots, y^{(k-1)}_n, p)) \), \((\alpha = 1,\ldots,k-1), (i, j = 1,2,\ldots,n)\) are the local coefficients of the nonlinear connection \( N \).
Then any $N$-linear connection, $D$, with the local coefficients $D\Gamma(N) = \left( H^{(\alpha)}_{j\beta}, C^{(\alpha)}_{i\beta}, C^{(\alpha)}_{i\beta} \right), (\alpha = 1, \ldots, k-1)$, can be expressed in the form \[13\]:

\[
\begin{align*}
H^{(\alpha)}_{j\beta} &= H^{(\alpha)}_{j\beta} - B^{(\alpha)}_{j\beta}, \\
C^{(\alpha)}_{i\beta} &= C^{(\alpha)}_{i\beta} - D^{(\alpha)}_{i\beta}, (\alpha = 1, \ldots, k-1), (k \geq 2, k \in N), \\
C^{(\alpha)}_{i\beta} &= C^{(\alpha)}_{i\beta} - D^{(\alpha)}_{i\beta}.
\end{align*}
\]

Using the relations (13), (16) and the Theorem 1 given by R. Miron in ([5]) for the case of Finsler connections we obtain:

**Theorem 2** Let $\hat{D}$ be a given $N$-linear connection, with local coefficients $\hat{D}\Gamma(N) = \left( H^{(\alpha)}_{j\beta}, C^{(\alpha)}_{i\beta}, C^{(\alpha)}_{i\beta} \right), (\alpha = 1, \ldots, k-1)$. The set of all general conformal almost symplectic $N$-linear connections, with respect to $\hat{A}$, corresponding to the same nonlinear connection $N$, with local coefficients $D\Gamma(N) = \left( H^{(\alpha)}_{j\beta}, C^{(\alpha)}_{i\beta}, C^{(\alpha)}_{i\beta} \right), (\alpha = 1, \ldots, k-1)$ is given by:

\[
\begin{align*}
H^{(\alpha)}_{j\beta} &= H^{(\alpha)}_{j\beta} + \frac{1}{2} a^{im}_{mjp} h^{(\alpha)}_{ij} - K^{(\alpha)}_{mjk} + \Omega^{(\alpha)}_{ij} X^i_{rh}, \\
C^{(\alpha)}_{i\beta} &= C^{(\alpha)}_{i\beta} + \frac{1}{2} a^{im}_{mjp} h^{(\alpha)}_{ij} - Q^{(\alpha)}_{ijh} + \Omega^{(\alpha)}_{ijh} Z^i_{rsh}, (\alpha = 1, \ldots, k-1), \\
C^{(\alpha)}_{i\beta} &= C^{(\alpha)}_{i\beta} + \frac{1}{2} a^{ml}_{mjp} h^{(\alpha)}_{ij} - \hat{Q}^{(\alpha)}_{ijkl} + \Omega^{(\alpha)}_{ijh} Z^i_{rsh},
\end{align*}
\]

Where $\frac{0}{h}$, and $\frac{h}{h}$ denote the $h-$, $v_{\alpha}$ – and $w_{\alpha}$ – covariant derivatives with respect to $\frac{0}{h}$, $X^{(\alpha)}_{j\beta}, Y^{(\alpha)}_{i\beta}, Z^{(\alpha)}_{i\beta}$ are arbitrary $d$-tensor fields and $K^{(\alpha)}_{ijh}, g^{(\alpha)}_{ijh}, \hat{Q}^{(\alpha)}_{ijh}$ are arbitrary $d$-tensor fields of the types $(0,3), (0,3)$ and $(2,1)$ respectively, with the properties $K^{(\alpha)}_{ijh}, g^{(\alpha)}_{ijh}, \hat{Q}^{(\alpha)}_{ijh}$ are arbitrary $d$-tensor fields.

**Particular cases:**

1. If we take $K^{(\alpha)}_{ijh} = 2\omega_{\alpha} a_{ij}, g^{(\alpha)}_{ijh} = 2\hat{\omega}_{\alpha} a_{ij}, (\alpha = 1, \ldots, k-1), \hat{Q}^{(\alpha)}_{ijh} = 2\hat{\omega}_{\alpha} a_{ij}$ in Theorem 2, we obtain:

**Theorem 3** Let $\hat{D}$ be a given $N$-linear connection, with local coefficients $D\Gamma(N) = \left( H^{(\alpha)}_{j\beta}, C^{(\alpha)}_{i\beta}, C^{(\alpha)}_{i\beta} \right), (\alpha = 1, \ldots, k-1)$.
The set of all conformal almost symplectic N-linear connections with respect to $\hat{A}$, corresponding to the 1-form $\omega$, with local coefficients $\hat{D}\Gamma(N,\omega) = \{ H^i_{\ jh}, C^i_{\ jh}, C^i_{\ jh} \}, (\alpha = 1, \ldots, k-1)$ is given by:

$$
\begin{align*}
H^i_{\ jh} &= H^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - 2 \omega_h a_{\ mj}) + \Omega^i_{\ jh}, \\
C^i_{\ jh} &= C^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - 2 \omega_h a_{\ mj}) + \Omega^i_{\ jh}, (\alpha = 1, \ldots, k-1), \\
C^i_{\ jh} &= C^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - 2 \omega_h a_{\ mj}) + \Omega^i_{\ jh}, (i, j, h = 1, 2, \ldots, n),
\end{align*}
$$

where $\partial_0^h$, $\|_h$ and $\partial_0^h$ denote the $h-$, $v_\alpha-$ and $w_k-$ covariant derivatives with respect to $D$, $X^i_{\ jh}$, $Y^i_{\ jh}$, $Z^i_{\ jh}$ are arbitrary d-tensor fields, $(\alpha = 1, \ldots, k-1)$, $\omega = \omega_i dx^i + \omega_h \delta^{(1)}_{(i)} + \ldots + \omega_k \delta^{(k-1)}_{(i)} + \omega \delta_i$, is an arbitrary 1-form and $\Omega$ is the operator of Obata's type given by (10).

2. If $X^i_{\ jh} = Y^i_{\ jh} = Z^i_{\ jh} = 0$, in Theorem 2 we have:

**Theorem 4** Let $D$ be a given N-linear connection, with local coefficients $\hat{D}\Gamma(N) = \{ H^i_{\ jh}, C^i_{\ jh}, C^i_{\ jh} \}, (\alpha = 1, \ldots, k-1)$. Then the following N-linear connection $K$, with local coefficients $\hat{K}\Gamma(N) = \{ H^i_{\ jh}, C^i_{\ jh}, C^i_{\ jh} \}, (\alpha = 1, \ldots, k-1)$, given by (19) is general conformal almost symplectic with respect to $\hat{A}$:

$$
\begin{align*}
H^i_{\ jh} &= H^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - K_{mjh}), \\
C^i_{\ jh} &= C^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - Q_{mjh}), (\alpha = 1, \ldots, k-1), \\
C^i_{\ jh} &= C^i_{\ jh} + \frac{1}{2} a^m (a_{\ mj\ h} - \hat{Q}_{mjh}), \\
\end{align*}
$$

where $\partial_0^h$, $\|_h$, and $\partial_0^h$ denote the $h-$, $v_\alpha-$ and $w_k-$ covariant derivatives with respect to $D$, and $K_{ih}, Q_{ih}, \hat{Q}_{ih}$ are arbitrary d-tensor fields of the types (0,3), (0,3) and (2,1) respectively, with the properties: $K_{ih} = K_{ih}, Q_{ih} = Q_{ih}, \hat{Q}_{ih} = \hat{Q}_{ih}, (\alpha = 1, \ldots, k-1)$.
3. If we take a general conformal almost symplectic N-linear connection with respect to \( \hat{A} \) as \( \hat{D} \), in Theorem 2 we have:

**Theorem 5** Let \( \hat{D} \) be on \( T^k M \) a fixed general conformal almost symplectic N-linear connection with respect to \( \hat{A} \), with the local coefficients

\[
\hat{D} \Gamma(N) = \left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

The set of all general conformal almost symplectic N-linear connections, with respect to \( \hat{A} \), with local coefficients

\[
\hat{D} \Gamma(N) = \left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

is given by:

\[
\left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

where \( X^i_{\ jh}, Y^i_{\ jh}, Z^i_{\ jh} \) are arbitrary d-tensor fields, \( (\alpha = 1, \ldots, k-1) \).

4. If \( K_{ijh} = Q_{ijh} = \hat{Q}_{ijh} = 0, (\alpha = 1, \ldots, k-1) \) in Theorem 2 we obtain the set of all almost symplectic N-linear connection in the case when the nonlinear connection is fixed:

**Theorem 6** Let \( \hat{D} \) be a given N-linear connection, with local coefficients

\[
\hat{D} \Gamma(N) = \left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

The set of all almost symplectic N-linear connections, with respect to \( \hat{A} \), corresponding to the same nonlinear connection \( N \), with local coefficients

\[
\hat{D} \Gamma(N) = \left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

is given by:

\[
\left\{ \begin{array}{c}
H^i_{\ jh} = H^i_{\ jh} + \frac{1}{2} a^m_{\ \ \ m} a^m_{\ \ \ mj} |^h + \Omega^s_{\ jh} X^s_i, \\
C^i_{(a)} = C^i_{(a)} + \frac{1}{2} a^m_{\ \ \ m} a^m_{\ \ \ mj} |^h + \Omega^s_{\ jh} Y^s_i, \\
C^i_{\ jh} = C^i_{\ jh} + \frac{1}{2} a^m_{\ \ \ m} a^m_{\ \ \ mj} |^h + \Omega^s_{\ jh} Z^s_i,
\end{array} \right. \quad (\alpha = 1, \ldots, k-1)
\]

where \( |^h, \ \ \ |^h \) denote the \( h- \), \( v_a- \) and \( w_k- \) covariant derivatives with respect to \( \hat{D} \), \( X^i_{\ jh}, Y^i_{\ jh}, Z^i_{\ jh} \) are arbitrary d-tensor fields.
Theorem 7 The mappings $\mathcal{D}\Gamma(N) \to \mathcal{D}\Gamma(N)$ determined by (20), together with the composition of these mappings is an abelian group.

REFERENCES