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$(\overset{1}{F}, \overset{2}{F})$- AND $(\overset{3}{F}, \overset{4}{F})$-CONNEXIONS OF AN ALMOST COMPLEX AND AN ALMOST PRODUCT SPACE

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1. *Introduction.* — In an almost complex space an affine connexion is called F-connexion if the almost complex structure tensor F_j^i is covariant constant with respect to this connexion. The general F-connexion has the form ([1], chapter VI, § 2):

$$\Gamma^k_{ji} = \overset{\circ}{\Gamma}{}^k_{ji} - \frac{1}{2}(\overset{\circ}{\nabla}_j F^a_i) F^k_a + \frac{1}{2}(\delta^a_i \delta^k_b - F^a_i F^k_b) W^b_{ja}, \tag{1.1}$$

where W^b_{ka} is an arbitrary tensor of the type indicated by the indices, and $\overset{\circ}{\nabla}$ denotes the covariant differentiation with respect to the symmetric affine connexion $\overset{\circ}{\Gamma}{}^k_{ji}$.

Similarly, the general connexion in the almost product space with respect to which the almost product structure F_j^i is covariant constant, has the form:

$$\Gamma^k_{ji} = \overset{\circ}{\Gamma}{}^k_{ij} + \frac{1}{2}(\overset{\circ}{\nabla}_j F^a_i) F^k_a + \frac{1}{2}(\delta^a_i \delta^k_b + F^a_i F^k_b) W^b_{ja}. \tag{1.2}$$

If we put

$$F^i_a F^a_j = \omega \delta^i_j, \qquad \omega = +1 \quad \text{or} \quad \omega = -1, \tag{1.3}$$

and if the operators O and $*O$ are defined by ([1]):

$$\begin{cases} O^{sh}_{ir} = \frac{1}{2}(\delta^s_i \delta^h_r + \omega F^s_i F^h_r), \\ *O^{sh}_{ir} = \frac{1}{2}(\delta^s_i \delta^h_r - \omega F^s_i F^h_r), \end{cases} \tag{1.4}$$

the equations (1.1) and (1.2) can be written in the from:

$$\Gamma^k_{ji} = \overset{\circ}{\Gamma}{}^k_{ji} + \frac{1}{2}\omega(\overset{\circ}{\nabla}_j F^a_i) F^k_a + O^{ak}_{ib} W^b_{ja}. \tag{1.5}$$

In (1.3), (1.4) and (1.5), $\omega = -1$ if the space is an almost complex space, and $\omega = +1$ if the space is an almost product space.

The connexion (1.5) being non-symmetric, we can consider four kinds of the covariant derivatives. These covariant derivatives, of a tensor a_j^i for example, are given by:

$$\overset{1}{\nabla}_k a_j^i = \frac{\partial a_j^i}{\partial x^k} + a_j^p \Gamma_{pk}^i - a_p^i \Gamma_{jk}^p,$$

$$\overset{2}{\nabla}_k a_j^i = \frac{\partial a_j^i}{\partial x^k} + a_j^p \Gamma_{kp}^i - a_p^i \Gamma_{kj}^p,$$

$$\overset{3}{\nabla}_k a_j^i = \frac{\partial a_j^i}{\partial x^k} + a_j^p \Gamma_{pk}^i - a_p^i \Gamma_{kj}^p,$$

$$\overset{4}{\nabla}_k a_j^i = \frac{\partial a_j^i}{\partial x^k} + a_j^p \Gamma_{kp}^i - a_p^i \Gamma_{jk}^p.$$

The connexion (1.5) is the general connexion satisfying the condition $\overset{2}{\nabla}_k F_j^i = 0$. In § 2 we shall discuss the possibility of finding the $(\overset{1}{F}, \overset{2}{F})$-connexion, i. e. the general affine connexion Γ_{ji}^k such that

$$\overset{1}{\nabla}_k F_j^i = \overset{2}{\nabla}_k F_j^i = 0, \tag{1.6}$$

and in § 3 the possibility of finding the $(\overset{3}{F}, \overset{4}{F})$-connexion, i. e. the general affine connexion Γ_{ji}^k such that

$$\overset{3}{\nabla}_k F_j^i = \overset{4}{\nabla}_k F_j^i = 0. \tag{1.7}$$

In § 4 we shall show that $(\overset{1}{F}, \overset{2}{F})$-connexion is, under some conditions, Rizza's ρ_+-connexion and $(\overset{3}{F}, \overset{4}{F})$-connexion is, under some conditions, Rizza's ρ_--connexion ([2], [3]) and conversely.

2. $(\overset{1}{F}, \overset{2}{F})$*-connexion.* — Putting

$$\Gamma_{ji}^k = \overset{\circ}{\Gamma}{}_{ji}^k + U_{ji}^k, \tag{2.1}$$

where

$$U_{ji}^k = \frac{1}{2} \omega (\overset{\circ}{\nabla}_j F_i^a) F_a^k + O_{ib}^{ak} W_{ja}^b, \tag{2.2}$$

we have

$$\overset{1}{\nabla}_k F_j^i = \overset{\circ}{\nabla}_k F_j^i + F_j^p U_{pk}^i - F_p^i U_{jk}^p,$$

$$\overset{2}{\nabla}_k F_j^i = \overset{\circ}{\nabla}_k F_j^i + F_j^p U_{pk}^i - F_p^i U_{kj}^p.$$

Thus, the condition (1.6) can be written in the form:

$$F_j^p (U_{kp}^i - U_{pk}^i) - F_p^i (U_{kj}^p - U_{jk}^p) = 0,$$

and consequently

$$(U_{kq}^p - U_{qk}^p) {}^*O_{pj}^{iq} = 0.$$

Substituting (2.2) into this equation, we get

$$\left[\frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_k F_q^a)\,F_a^p + O_{qb}^{ap}\,W_{ka}^b - \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_q F_k^a)\,F_a^p - O_{kb}^{ap}\,W_{qa}^b\right]{}^*O_{pj}^{iq} = 0.$$

Taking into account that $O_{qb}^{ap}\cdot{}^*O_{pj}^{iq} = 0$, the last equation reduces to

$$\left[\frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_k F_q^a)\,F_a^p - \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_q F_k^a)\,F_a^p - O_{kb}^{ap}\,W_{qa}^b\right]{}^*O_{pj}^{iq} = 0.$$

Using Yano's lemma ([1], p. 133), we have

$$\frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_k F_q^a)\,F_a^p - \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_q F_k^a)\,F_a^p - O_{kb}^{ap}\,W_{qa}^b = O_{qb}^{ap}\,V_{ka}^b.$$

V_{ka}^b being an arbitrary tensor, we can put

$$V_{ka}^b = -W_{ak}^b.$$

Thus we obtain:

$$(\overset{\circ}{\nabla}_k F_q^a - \overset{\circ}{\nabla}_q F_k^a)\,F_a^p - (W_{qa}^b\,F_k^a - W_{ak}^b\,F_q^a)\,F_b^p = 0.$$

Contraction by $F_p^i F_j^k$ gives

$$(2.3)\qquad {}^*O_{qj}^{ab}\,W_{ab}^i = \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_a F_q^i - \overset{\circ}{\nabla}_q F_a^i)\,F_j^a.$$

The equation (2.3) admits a solution, by virtue of the Yano's lemma ([1], p. 133), if and only if:

$$O_{qj}^{ab}\,(\overset{\circ}{\nabla}_t F_a^i - \overset{\circ}{\nabla}_a F_t^i)\,F_b^t = (\overset{\circ}{\nabla}_a F_q^i - \overset{\circ}{\nabla}_q F_a^i)\,F_j^a - (\overset{\circ}{\nabla}_a F_j^i - \overset{\circ}{\nabla}_j F_a^i)\,F_q^a = N_{jq}^i = 0,$$

i. e. iff the structure is integrable. Then the general solution of (2.3) is given by

$$(2.4)\qquad W_{ja}^b = \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_t F_j^b - \overset{\circ}{\nabla}_j F_t^b)\,F_a^t + O_{ja}^{rs}\,A_{rs}^b,$$

where A_{rs}^b is an arbitrary tensor.

Substituting (2.4) into (1.5), we have

$$\Gamma_{ji}^k = \overset{\circ}{\Gamma}{}_{ji}^k + \frac{1}{2}\,\omega\,(\overset{\circ}{\nabla}_j F_i^a)\,F_a^k + \frac{1}{2}\,\omega\,O_{ib}^{ak}\,(\overset{\circ}{\nabla}_t F_j^b - \overset{\circ}{\nabla}_j F_t^b)\,F_a^t + O_{ib}^{ak}\,A_{ja}^{rs}A_{rs}^b,$$

or

$$(2.5)\qquad \begin{aligned}\Gamma_{ji}^k = \overset{\circ}{\Gamma}{}_{ji}^k &+ \frac{1}{4}\,\omega\,[(\overset{\circ}{\nabla}_a F_j^k - \overset{\circ}{\nabla}_j F_a^k)\,F_i^a + (\overset{\circ}{\nabla}_i F_j^a + \overset{\circ}{\nabla}_j F_i^a)\,F_a^k]\\ &+ A_{ji}^k + \omega\,A_{ai}^b\,F_j^a\,F_b^k + \omega\,A_{ja}^b\,F_i^a\,F_b^k + \omega\,A_{ab}^k\,F_j^a\,F_i^b.\end{aligned}$$

$\left(A_{ji}^k \text{ being arbitrary, we have put } A_{ji}^k \text{ instead of } \frac{1}{4}A_{ji}^k\right).$

Let T^k_{ji} be the torsion tensor of the connexion

$$\overset{\circ}{\Gamma}{}^k_{ji} + \frac{1}{4}\,\omega\,[(\overset{\circ}{\nabla}_a F^k_j - \overset{\circ}{\nabla}_j F^k_a)\, F^a_i + (\overset{\circ}{\nabla}_i F^a_j + \overset{\circ}{\nabla}_j F^a_i)\, F^k_a]. \tag{2.6}$$

Then

$$T^k_{ji} = \frac{1}{4}\,\omega\,[(\overset{\circ}{\nabla}_a F^k_j - \overset{\circ}{\nabla}_j F^k_a)\, F^a_i - (\overset{\circ}{\nabla}_a F^k_i - \overset{\circ}{\nabla}_i F^k_a)\, F^a_j] = \frac{1}{4}\,\omega\, N^k_{ij} = O,$$

i.e. (2.6) is a symmetric connexion. It will be easily verified that (2.6) is an F-connexion. Thus we can consider, instead of (2.5), the connexion

$$\Gamma^k_{ji} = \overset{\circ}{\Gamma}{}^k_{ji} + A^k_{ji} + \omega\, A^b_{ai} F^a_j F^k_b + \omega\, A^b_{ja} F^a_i F^k_b + \omega\, A^k_{ab} F^a_j F^b_i, \tag{2.7}$$

where $\overset{\circ}{\Gamma}{}^k_{ji}$ is a symmetric F-connexion and A^k_{ji} is an arbitrary tensor.

Thus we have the theorem:

In order that in an almost complex space or in an almost product space there exists a $(\overset{1}{F}, \overset{2}{F})$*-connexion, it is necessary and sufficient that the structure be integrable. Then the general* $(\overset{1}{F}, \overset{2}{F})$*-connexion has the form* (2.7).

3. $(\overset{3}{F}, \overset{4}{F})$*-connexion.* — An arbitrary affine connexion may be written as

$$\Gamma^k_{ji} = \overset{\circ}{\Gamma}{}^k_{ji} + A^k_{ji}, \tag{3.1}$$

where $\overset{\circ}{\Gamma}{}^k_{ji}$ is a symmetric affine connexion, and A^k_{ji} is an arbitrary tensor. Then

$$\overset{3}{\nabla}_k F^i_j = \overset{\circ}{\nabla}_k F^i_j + F^p_j A^i_{pk} - F^i_p A^p_{kj},$$

and the condition $\overset{3}{\nabla}_k F^i_j = 0$ is equivalent to

$$F^p_j A^i_{pk} - F^i_p A^p_{kj} + \overset{\circ}{\nabla}_k F^i_j = 0. \tag{3.2}$$

Transvecting (3.2) with F^j_t and with F^t_i, we find respectively

$$\omega\, A^b_{ka} F^a_j F^i_b = A^i_{jk} + \omega\,(\overset{\circ}{\nabla}_k F^i_a)\, F^a_j, \tag{3.3}$$

$$\omega\, A^b_{ak} F^a_j F^i_b = A^i_{kj} - \omega\,(\overset{\circ}{\nabla}_k F^a_j)\, F^i_a. \tag{3.4}$$

Multiplying (3.3) by $F^j_r F^k_s$, we obtain

$$A^b_{kr} F^i_b F^k_s = A^i_{jk} F^j_r F^k_s + (\overset{\circ}{\nabla}_a F^i_r)\, F^a_s.$$

Substituting (3.4) into this equation, we have

$$\omega\, A^i_{ba} F^b_k F^a_j = A^i_{kj} - \omega\,(\overset{\circ}{\nabla}_k F^a_j)\, F^i_a - \omega\,(\overset{\circ}{\nabla}_a F^i_k)\, F^a_j, \tag{3.5}$$

and consequently

$$\frac{1}{2} A^i_{ba} {*O}^{ba}_{kj} = \omega\,[(\overset{\circ}{\nabla}_k F^a_j)\, F^i_a + (\overset{\circ}{\nabla}_a F^i_k)\, F^a_j].$$

This equation admits, by the mentioned lemma ([1], p. 133), the solution if and only if

$$[(\overset{\circ}{\nabla}_k F_j^a)\, F_a^i + (\overset{\circ}{\nabla}_a F_k^i)\, F_j^a]\, O_{rs}^{kj} = 0,$$

i. e. if and only if

$$(\overset{\circ}{\nabla}_a F_r^i - \overset{\circ}{\nabla}_r F_a^i)\, F_s^a - (\overset{\circ}{\nabla}_a F_s^i - \overset{\circ}{\nabla}_s F_a^i)\, F_r^a = N_{sr}^i = 0. \tag{3.6}$$

This condition shows that the structure F_j^i must be integrable.

Combining (3.3), (3.4) and (3.5), we get

$$4\, A_{kj}^i - 2\,\omega\, (\overset{\circ}{\nabla}_k F_j^a)\, F_a^i + \omega\, (\overset{\circ}{\nabla}_j F_a^i)\, F_k^a - \omega\, (\overset{\circ}{\nabla}_a F_k^i)\, F_j^a =$$

$$= A_{kj}^i + \omega\, A_{ja}^b\, F_k^a\, F_b^i + \omega\, A_{ak}^b\, F_j^a\, F_b^i + \omega\, A_{ba}^i\, F_k^b\, F_j^a,$$

i. e.

$$A_{kj}^i = \frac{1}{4}\, (A_{kj}^i + \omega\, A_{ja}^b\, F_k^a\, F_b^i + \omega\, A_{bk}^a\, F_j^b\, F_a^i + \omega\, A_{ba}^i\, F_k^b\, F_j^a) +$$

$$+ \frac{\omega}{2}\, (\overset{\circ}{\nabla}_k F_j^a)\, F_a^i - \frac{\omega}{4}\, (\overset{\circ}{\nabla}_j F_a^i)\, F_k^a + \frac{\omega}{4}\, (\overset{\circ}{\nabla}_a F_k^i)\, F_j^a.$$

Substituting this into (3.1), we find

$$\Gamma_{kj}^i = \overset{\circ}{\Gamma}{}_{kj}^i + \frac{\omega}{2}\, (\overset{\circ}{\nabla}_k F_j^a)\, F_a^i - \frac{\omega}{4}\, (\overset{\circ}{\nabla}_j F_a^i)\, F_k^a + \frac{\omega}{4}\, (\overset{\circ}{\nabla}_a F_k^i)\, F_j^a +$$

$$+ A_{kj}^i + \omega\, A_{ja}^b\, F_k^a\, F_b^i + \omega\, A_{bk}^a\, F_j^b\, F_a^i + \omega\, A_{ba}^i\, F_k^b\, F_j^a,$$

where $\overset{\circ}{\Gamma}{}_{kj}^i$ is a symmetric connexion satisfying (3.6) and where we have put, A_{ji}^k being arbitrary, A_{ji}^k instead of $\frac{1}{4}\, A_{ji}^k$.

Let us consider the connexion

$$\overset{\circ}{\Gamma}{}_{kj}^i + \frac{\omega}{2}\, (\overset{\circ}{\nabla}_k F_j^a)\, F_a^i - \frac{\omega}{4}\, (\overset{\circ}{\nabla}_j F_a^i)\, F_k^a + \frac{\omega}{4}\, (\overset{\circ}{\nabla}_a F_a^i)\, F_j^a. \tag{3.8}$$

It is an F-connexion, and its torsion tensor

$$\frac{\omega}{4}\, [(\overset{\circ}{\nabla}_a F_k^i - \overset{\circ}{\nabla}_k F_a^i)\, F_j^a - (\overset{\circ}{\nabla}_a F_j^i - \overset{\circ}{\nabla}_j F_a^i)\, F_k^a] = \frac{\omega}{4}\, N_{jk}^i$$

vanishes. This means that we can consider, instead of (3.7), the connexion

$$\Gamma_{kj}^i = \overset{\circ}{\Gamma}{}_{kj}^i + A_{kj}^i + \omega\, A_{ja}^b\, F_b^i\, F_k^a + \omega\, A_{bk}^a\, F_j^b\, F_a^i + \omega\, A_{ba}^i\, F_k^b\, F_j^a, \tag{3.9}$$

where $\overset{\circ}{\Gamma}{}_{kj}^i$ is a symmetric F-connexion.

In exactly the same way we can prove that (3.9) is the general connexion satisfying the condition $\overset{4}{\nabla}_k F_j^i = 0$ too. Thus we have the theorem:

In order that in an almost complex space or in an almost product space there exists a $(\overset{3}{F}, \overset{4}{F})$*-connexion, it is necessary and sufficient that the structure be integrable. Then the general* $(\overset{3}{F}, \overset{4}{F})$*-connexion has the form* (3.9).

4. *Rizza's* ρ_+*- and* ρ_-*-connexions.* — G. B. Rizza ([2]) defined ρ_+- and ρ_--connexion in an almost complex space in the following manner.

We can consider, in the tangent space at each point of the manifold with an almost complex structure F_j^i, the transformations:

$$J_\varphi : J_\varphi(U^i) = U^i \cos\varphi + F_a^i U^a \sin\varphi \qquad (0 \leqslant \varphi \leqslant 2\pi). \tag{4.1}$$

The torsion of a non-symmetric connexion is the skew-symmetric tensor. Conversely, every skew-symmetric tensor S_{ij}^k can be considered as the torsion tensor of a non-symmetric connexion. Let us put

$$\Omega^k(U, V) = -2 S_{ij}^k U^i V^j, \tag{4.2}$$

where U and V are linearly independent vectors. Applying to U and V the transformation J_φ, we may construct the corresponding vector (4.2):

$$\Omega^k(J_\varphi U, J_\varphi V) = -2 S_{ij}^k J_\varphi(U^i) J_\varphi(V^i).$$

On the other hand, we can apply the transformation J_φ to the vector $\Omega^k(U, V)$. G. B. Rizza discusses ([2], [3]) the possibility of finding a skew-symmetric tensor S_{ij}^k such that

$$\Omega^k(J_\varphi U, J_\varphi V) = J_\psi \Omega^k(U, V) \tag{4.3}$$

for arbitrary vectors U, V and where ψ is a function of φ. He showed that

$$\text{either } \psi = +2\varphi, \quad \text{or} \quad \psi = -2\varphi, \quad \text{or} \quad \psi = 0.$$

The connexion whose torsion tensor satisfies (4.3) such that $\psi = +2\varphi$ is called an ρ_+-connexion. The general ρ_+-connexion has the form ([3]):

$$\Gamma_{ij}^k = \overset{\circ}{\Gamma}{}_{ij}^k + A_{ij}^k + \omega A_{aj}^b F_i^a F_b^k + \omega A_{ia}^b F_j^a F_b^k + \omega A_{ab}^k F_i^a F_k^b, \tag{4.4}$$

where $\omega = -1$, $\overset{\circ}{\Gamma}{}_{ij}^k$ is an arbitrary symmetric connexion and A_{ij}^k is an arbitrary skew-symmetric tensor.

The connexion whose torsion tensor satisfies (4.3) such that $\psi = -2\varphi$ is called an ρ_--connexion. The general ρ_--connexion has the form ([3]):

$$\Gamma_{ij}^k = \overset{\circ}{\Gamma}{}_{ij}^k + A_{ij}^k + \omega A_{ai}^b F_j^a F_b^k + \omega A_{ja}^b F_i^a F_b^k + \omega A_{ab}^k F_i^a F_j^b, \tag{4.5}$$

where ω, $\overset{\circ}{\Gamma}{}_{ij}^k$ and A_{ij}^k have the same meaning as before.

To define ρ_+- and ρ_--connexion in an n-dimensional almost product space, we first remember that the structure tensor F_i^j of a such space defines two complementary distributions in the n-dimensional tangent plane at each point of the space. Let us suppose that the vector U does not belong to either of these distributions. Then U^i and $F_a^i U^a$ are linearly independent vectors and we can consider, instead of (4.1), the transformations:

$$J_\varphi : J_\varphi(U^i) = U^i \operatorname{ch}\varphi + F_a^i U^a \operatorname{sh}\varphi. \tag{4.6}$$

Supposing that the vector (4.2) does not belong to either of distributions, we may consider the vector $J_\psi \Omega^k(U, V)$ and then also the condition (4.3), where U and V are linearly independent vectors.

The connexion in an almost product space whose torsion tensor satisfies (4.3) for arbitrary vectors U, V (where J_φ is the transformation (4.6)), such that $\psi = +2\varphi$ is called an ρ_+-connexion, and that whose torsion tensor satisfies (4.3) such that $\psi = -2\varphi$ is called an ρ_--connexion. In exactly the same way as in [2] and [3], we obtain that the general ρ_+-connexion in an almost product space has the form (4.4) (where $\omega = +1$), and the general ρ_--connexion has the form (4.5) ($\omega = +1$).

Comparing (4.4) and (2.7), (4.5) and (3.9), we see that:

$(\overset{1}{F}, \overset{2}{F})$*-connexion* (2.7) *in a complex space* (*in a product space*) *where arbitrary tensor* A^i_{jk} *is skew-symmetric is an* ρ_+*-connexion. Conversely, an* ρ_+*-connexion* (4.4) *where* $\overset{\circ}{\Gamma}{}^k_{ij}$ *is a symmetric F-connexion, is an* $(\overset{1}{F}, \overset{2}{F})$*-connexion.*

$(\overset{3}{F}, \overset{4}{F})$*-connexion* (3.9) *in a complex* (*in a product*) *space, where* A^i_{jk} *is an arbitrary skew-symmetric tensor, is an* ρ_-*-connexion. Conversely, an* ρ_-*-connexion* (4, 5), *where* $\overset{\circ}{\Gamma}{}^i_{jk}$ *is a symmetric F-connexion, is an* $(\overset{3}{F}, \overset{4}{F})$*-connexion.*

The ρ_+- and ρ_--connexions in an almost product space cannot be determined if the vector (4.2) belongs to one of the distributions. Thus, we have yet to determine, in the case $\omega = +1$, the condition satisfied by torsion tensor S^i_{jk}, if the vector (4.2) belongs to one of the distributions.

If the vector W belongs to one of the distributions then either $W^i = F^i_a W^a$ or $W^i = -F^i_a W^a$. This means, in the case of the vector $S^i_{jk} U^j V^k$, that

$$S^i_{jk} U^j V^k = \pm F^i_a S^a_{jk} U^j V^k$$

for every pair U, V. Consequently

$$S^i_{jk} = \pm F^i_a S^a_{jk}.$$

This is the required condition.

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