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ON GROUPS OF ROTATIONS IN MINKOWSKI SPACE I

By

Tamao NAGAI

§1. Introduction. Let $F_{n+1}$ be an $n+1$-dimensional Finsler space with the fundamental function $F(x^{i}, x'^{i}) (i=1, 2, \cdots, n+1)$. At every point with coordinate $(x'^{i})$ in $F_{n+1}$, we obtain an $n+1$-dimensional Minkowski space $M_{n+1}$, whose indicatrix $I_{n}$ is given by the end points of the vectors $(X^{i})$'s at the origin $(x'^{i})$ satisfying the equation

(1.1) $g_{ij}(x^{i}, X)X^{i}X^{j} = 1 \quad (g_{ij}(x, X) = \frac{1}{2} \partial^{2}F(x, X)/\partial X^{i}\partial X^{j})$.

At any point $(x'^{i})$, the quadratic form for any fixed vector $X'_{0}$:

(1.2) $g_{ij}(x^{i}, X'_{0})X^{i}X^{j} = 1$

defines a hyperquadric $I^{*}_{n}$ which is in double contact with $I_{n}$ at two points of coordinates $(X'_{0})$ and $(-X'_{0})$ respectively.

L. Berwald [5], E. Cartan [6] and many others regarded a Finsler space as a space of line-elements $(x^{i}, x'^{i})$. From this point of view, we can obtain for each line-element $(x'^{i}_{0}, x'^{i}_{0})$ an $n+1$-dimensional tangent Euclidean space $E_{n+1}(x'^{i}_{0}, x'^{i}_{0})$ whose indicatrix is a hyperquadric $I^{*}_{n}$ determined by (1.2) by putting $X'_{0} = x'^{i}_{0}$. Under this consideration the connection in $F_{n+1}$ was established by defining a suitable correspondence between neighbouring tangent Euclidean spaces $E_{n+1}^{1}(x^{i}, x'^{i})$ and $E_{n+1}(x^{i}+dx^{i}, x'^{i}+dx'^{i})$.

Recently W. Barthel [1]-[4], A. Kawaguchi [9], D. Laugwitz [10] and H. Rund [11] reconstructed the foundation of the theory of Finsler space from the stand point that the Finsler space is a point space but is not a line-element space, that is to say, the tangent space at each point $(x'^{i})$ in $F_{n+1}$ should be regarded as a Minkowski space with an Indicatrix determined by $F(x'^{i}, X'_{0}) = 1$. On account of this fact, in order to establish the theory of Finsler space, it becomes an important problem to study

1) For the sake of convenience, we suppose that the dimension of a Finsler space is $n+1$, because in the present paper we shall discuss mainly about the theory of transformations in an $n$-dimensional indicatrix $I_{n}$.

2) Numbers in brackets refer to the references at the end of the paper.
the properties of Minkowski space. However since the foundation of the theory of Minkowski space depends on the structure of the indicatrix, it is necessary for us to study the properties of indicatrix in Minkowski space. From this point of view, A. Kawaguchi [9] and T. Sumitomo [12] developed the reduction theorems of Finsler space, namely, they gave various conditions by which the Finsler space can be regarded essentially as a Riemannian space and also gave interesting geometrical meanings of them. One of those results showed us that a Lie group of rotations is intransitive on $I_n$ and if it is transitive, the Minkowski space $M_{n+1}$ is to be euclidean in essential and then the considered Finsler space $F_{n+1}$ may be regarded as a Riemannian space, where the rotation means a centro-affine transformation in $M_{n+1}$ which leaves invariant the indicatrix $I_n$.

The present author wishes to study more precisely the properties of a Lie group of rotations. As will be shown in §3, $I_n$ may be regarded as an $n$-dimensional compact Riemannian space whose metric tensor is naturally induced from the metric of $M_{n+1}$ and it is remarkable that the Riemannian space admits a symmetric covariant tensor of order three. In the present paper we shall study, in an $n$-dimensional compact Riemannian space $I_n$, the properties of point transformations which are induced on $I_n$ by rotations in $M_{n+1}$.

In §2 the fundamental concepts of Minkowski space will be given and we shall give a definition of a rotation in $M_{n+1}$. §3 devoted to show some characters of an $n$-dimensional compact Riemannian space $I_n$. In §4, we will show that an infinitesimal point transformation $\bar{u}^\alpha = u^\alpha + \gamma^\alpha(u) \delta t$ coincides with the transformation induced on $I_n$ by an infinitesimal rotation in $M_{n+1}$ when the condition $\mathfrak{L}g_{\alpha\beta} = 2\gamma^\rho A_{\alpha\beta\gamma}$ be satisfied, where $\mathfrak{L}$ denotes Lie differential with respect to the above stated infinitesimal transformation and $A_{\alpha\beta\gamma}$ is a component of a symmetric covariant tensor defined in $I_n$. Since Lie differential is a main tool in our discussion, §5 devoted to give some formulas on Lie derivatives and several fundamental relations which will be useful in the following discussions.

When an indicatrix admits an intransitive group of rotation, it becomes an interesting problem to study the connection between structures of the indicatrix and those of the intransitive group. An example will be given in §6 to show some those connections. The integrability conditions of the infinitesimal point transformation, induced on $I_n$ by an infinitesimal rotation in $M_{n+1}$, are given in §7. §8 contains some
theorems concerning with properties of infinitesimal transformations in $I_n$, and also several characters of Lie group of the transformations will be given at the end of § 8.

The present author wishes to express his sincere thanks to Dr. A. Kawaguchi and Dr. Y. Katsurada for their constant guidances and criticisms, and also thanks to Mr. T. Sumitomo who gave the author many valuable suggestions.

§ 2. Preliminaries and definition of rotation in $M_{n+1}$. Minkowski space $M_{n+1}$ is an $n+1$-dimensional affine space in which the distance between two points $P=(P^1, P^2, \cdots, P^{n+1})$ and $Q=(Q^1, Q^2, \cdots, Q^{n+1})$ be determined by $F(Q-P)$. In the present paper we put the following assumptions about the function $F(X)\equiv F(X^1, X^2, \cdots, X^{n+1})$:

(I) $F(X)>0$ for $X \equiv 0$,

(II) $F(X)=F(-X)$,

(III) $F(\rho X)=\rho F(X)$ for $\rho > 0$,

(IV) $F(X)+F(Y)>F(X+Y)$ for linearly independent vectors $X$ and $Y$,

(V) $F(X)$ is continuous and continuously differentiable sufficiently many times,

(VI) regular, i.e. the matrix of

$$g_{jk}(X)=\frac{\partial^2 L}{\partial X^j \partial X^k} \quad (j, k=1, 2, \ldots, n+1)^3$$

has rank $n+1$, where $L=\frac{1}{2}F^2$.

In $M_{n+1}$ the indicatrix is given by the equation

(2.1) $F(X^1, X^2, \cdots, X^{n+1})=1$, 

namely, $I_n$ is an $n$-dimensional hypersurface consisting of all points $X=(X^i, X^2, \cdots, X^{n+1})$ which satisfy (2.1), where $X^i$ be regarded as coordinates of the end point of the radius vector at the origin $O=(0, 0, \cdots, 0)$ of the coordinate system.

Let us consider any centro-affine transformation $A_0$ in $M_{n+1}$, whose centre coincides with the origin $O=(0, 0, \cdots, 0)$, i.e.

(2.2) $A_0: \overline{X}^i=a_j^i X^j \quad (a_j^i=\text{const. and det. } |a_j^i| \equiv 0)$.

If the relation $F(\overline{X})=F(X)$ holds good for any vectors $X^i$ and $\overline{X}^i$, that is to say, the indicatrix $I_n$ remains unaltered under a transformation $A_0$.

3) Throughout the present paper the Latin indices $i, j, k, \cdots$ are supposed to run over the range 1, 2, $\cdots$, $n+1$. 

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we call the transformation the rotation in \( M_{n+1} \). Denoting by
\[
(2.3) \quad \overline{X}^i = (\delta_j^i + \xi_j^i \partial t)X^j = X^i + \xi_j^i X^j \partial t
\]
the infinitesimal transformation of the centro-affine transformation \( A_0 \), we find that \( \xi_j^i X^j \) is a vector which gives a general infinitesimal transformation of \( A_0 \).

Now, putting \( C_{ijk}(X) = \frac{1}{2} \frac{\partial g_{ij}}{\partial X^k} \), \( C_{ijk} \) is a component of a symmetric covariant tensor. Then, as we have
\[
\left\{ \begin{array}{c} i \\ jk \end{array} \right\} = \frac{1}{2} g^{ih} \left( \frac{\partial g_{hk}}{\partial X^j} + \frac{\partial g_{jh}}{\partial X^k} - \frac{\partial g_{jk}}{\partial X^h} \right) = C_{jk}^i
\]
we can define a covariant derivative of a tensor \( T_{jk}^i \) by
\[
(2.4) \quad T_{jk|l}^i = \frac{\partial T_{jk}^i}{\partial X^l} + T_{jk}^h C_{hl}^i - T_{hk}^i C_{il}^h - T_{jh}^i C_{kl}^h
\]
Making use of the covariant derivative, we can obtain the Lie derivative of a tensor \( T_{jk}^i \) with respect to an infinitesimal transformation \( \overline{X}^i = X^i + \xi^i(X) \partial t \) as follows:
\[
(2.5) \quad XT_{jk}^i = T_{jk|l}^i \xi^l - T_{jk}^l \xi_1^i + T_{lk}^i \xi|_j + T_{lj}^i \xi|_k
\]
Accordingly, for a generating vector \( \xi_j^i X^j \) we have from (2.4)
\[
(2.6) \quad (\xi_j^i X^j)_{1l} = \xi_l^i + \xi_j^h X^j C_{hl}^i
\]
From the definition, rotation in \( M_{n+1} \) is characterized by the equation \( Xg_{ij} = 0 \). Making use of (2.5) and (2.6) we find that
\[
(2.7) \quad Xg_{ij} = g_{ki} \xi_j^k + g_{kj} \xi_i^k + 2C_{ijk} \xi_l^k X^l = 0
\]
must be satisfied for an infinitesimal rotation.

The last equation is also obtained by the following way. By virtue of the assumptions (III), (IV) and (V), we can see that the covariant vector \( X_j = g_{jk}(X)X^k \) represents a hyperplane which is parallel to a hyperplane tangent to the indicatrix \( I_n \) at the point \( (X^i) \). On the other hand if we put
\[
(2.8) \quad Y_k = \frac{1}{F} \frac{\partial F}{\partial X^k} = \frac{1}{2L} g_{kj} X^j
\]
we find that the equation of the indicatrix \( I_n \) can be expressed by \( X^k Y_k = 1 \), where \( X^k \) denotes current coordinate. Then if the point \( (X^i) \) lies on the indicatrix, (2.8) gives us the relation
\[
(2.9) \quad Y_k = X_k = \frac{\partial F}{\partial X^k}
\]
According to the definition of rotation, $F(X)$ is an absolute invariant of an infinitesimal transformation (2.3). Then, by means of (2.9) it should be satisfied that

\begin{equation}
XF = \xi^k X' X_k = g_{kn} \xi^k X' X^m = 0.
\end{equation}

Since $g_{ij}(X^h)$ is homogeneous of degree zero with respect to $X^h$, $C_{ijk}(X)X^k = 0$ holds good. Therefore, differentiating the relation (2.10) with respect to $X^i$ and $X^j$, we obtain (2.7).

As $C_{ijk}(X)$ is a symmetric tensor, by means of (2.4)–(2.7) we can easily see that

\begin{equation}
XC_{jk}^i = \frac{1}{2} g^{ih} \{(Xg_{jh})_{|k} + (Xg_{hk})_{1j} - (Xg_{jk})_{|h}\}
\end{equation}

Therefore, if $Xg_{hj}=0$ holds good, we have $XC_{ijk}=0$.

**Theorem 2.1.** An infinitesimal rotation leaves invariant the symmetric tensor $C_{ijk}$.

A set of all rotations forms a subgroup of a group of centro-affine transformations. If the indicatrix $I_n$ admits an r-parameter Lie group $G_\tau$ of the rotations, its point is a fixed point of $G_\tau$ or lies on one of the family of affine $W$-submanifolds determined by $G_\tau$. According to the remarkable fact obtained by A. Kawaguchi [9], if $G_\tau$ is transitive on the indicatrix, it is an affine $W$-hypersurface and because of our assumptions stated in §2, the indicatrix must be a hyper-ellipsoid. Then, the considered Minkowski space is to be euclidean in essential. This is the fundamental conclusion for our following discussions.

**§ 3. Indicatrix of Minkowski space.** For the convenience of our discussion, following to the study of A. Kawaguchi [9] we shall give some fundamental properties of Riemannian space $I_n$. As indicatrix $I_n$ is an $n$-dimensional hypersurface in an $n+1$-dimensional Minkowski space $M_{n+1}$, we may express the indicatrix $I_n$ by $n+1$ equations involving $n$ parameters as

\begin{equation}
X^i = X^i(u^\alpha). \quad (i=1, 2, \cdots, n+1; \quad \alpha=1, 2, \cdots, n)^4.
\end{equation}

This means that we can regard $I_n$ as an $n$-dimensional manifold with coordinate system $(u^\alpha)$. According to (2.9), if the point $(X^i)$ lies on $I_n$, the equation of $I_n$ is reduced to $X_i X^i = 1$. Thus we get

4) Throughout the present paper, the Greek indices $\alpha, \beta, \gamma, \cdots$ take the values 1, 2, \ldots, $n$. 

\begin{equation}
3.2 \quad X_iX^i = 0. \quad \left( X^i = \frac{\partial X^i}{\partial u^\alpha}, \text{ Rank} \left( \frac{\partial X^i}{\partial u^\alpha} \right) = n \right)
\end{equation}

From the assumptions (I), (III), (V) and (VI), if we put $g_{\alpha \beta}(u) = g_{ij}(X)X^i X^j$, the indicatrix $I_n$ may be regarded as an $n$-dimensional compact Riemannian space whose fundamental metric tensor is $g_{\alpha \beta}(u)$. In consequence of (3.2), $n + 1$ vectors $X^i$ and $X^i$ are linearly independent and they form an ennuple $(X^i, X^i)$ at every point on $I_n$. As usual, putting
\begin{equation}
(3.3) \quad \frac{1}{F} C_{ijk} = \frac{1}{2F} \frac{\partial g_{ij}}{\partial X^k} = A_{ijk},
\end{equation}
it is evident that $C_{ijk} = A_{ijk}$ holds good at every point on $I_n$. If we denote by $A_{\alpha \beta \gamma}$ the induced quantity of the symmetric tensor $A_{ijk}$, then it follows that
\begin{equation}
(3.4) \quad A_{\alpha \beta \gamma} = A_{ijk} X^i X^j X^k, \quad A_{ijk} = A_{\alpha \beta \gamma} X^i X^j X^k,
\end{equation}
where $X^i = X_{\alpha \beta} X^i$ and $X_{\alpha \beta} = g_{\alpha \gamma} X^i$.
Denoting by $X^a_{\alpha \beta}$ and $X_{\alpha \beta}$ the covariant derivatives of $X^i$ and $X_a$ with respect to the Christoffel symbols constructed by $g_{\alpha \beta}$, we have the following decompositions with respect to the ennuple $(X^i, X^i)$:
\begin{align}
(3.5) \quad X^a_{\alpha \beta} &= -A_{\alpha \beta \gamma} X^i - g_{\alpha \beta} X^i, \\
(3.6) \quad X_{\alpha \beta} &= -A_{\alpha \beta \delta} X^i - g_{\alpha \beta} X^i,
\end{align}
where $A_{\alpha \beta \gamma} = A_{\alpha \beta \gamma} g^\gamma$.

Making use of (3.5), by means of the Ricci's identity $X^a_{\beta \gamma \delta} = X^a_{\beta \delta \gamma}$, we can easily obtain
\begin{equation}
(3.7) \quad R_{\alpha \beta \gamma \delta} = S_{\alpha \beta \gamma \delta} + (g_{\alpha \gamma} g_{\beta \delta} - g_{\alpha \delta} g_{\beta \gamma})
\end{equation}
where $R_{\alpha \beta \gamma \delta} = g_{\alpha \gamma} R_{\beta \gamma \delta}$ and
\begin{align}
R_{\alpha \beta \gamma \delta} &= g_{\alpha \gamma} R_{\beta \gamma \delta} \\
S_{\alpha \beta \gamma \delta} &= A_{\alpha \gamma \beta} A_{\alpha \gamma \beta} - A_{\alpha \gamma \beta} A_{\alpha \gamma \beta},
\end{align}

It is remarkable that, by virtue of (3.3) and (3.4), $A_{\alpha \gamma \beta}$ is a component of a symmetric tensor in $I_n$ and also it satisfies the relation
\begin{equation}
(3.8) \quad A_{\alpha \beta \gamma \delta ; \delta} = A_{\alpha \beta \gamma ; \delta}.
\end{equation}

Summarizing the preceding results, since $I_n$ is closed, we can regard the indicatrix $I_n$ as an $n$-dimensional compact Riemannian space, provided

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5) Throughout the present paper, semi-colon is used to represent covariant differentiation with respect to the Christoffel symbols made by $g_{\alpha \beta}$.
that there exists a symmetric tensor $A_{\alpha\beta\gamma}$ which satisfies the relation (3.8), and the curvature tensor has the form (3.7).

§ 4. **Infinitesimal rotation on $I_n$.** According to the definition given in § 2, the rotation transforms any point on the indicatrix $I_n$ onto the point on the same. Now, we shall seek the condition under which an infinitesimal point transformation $\overline{u}^\alpha = u^\alpha + \eta^\alpha(u) \delta t$ on $I_n$ coincides with rotation in $M_{n+1}$.

In consequence of (2.10), it follows that a direction of the generating vector $\xi_j^i X^j$ of an infinitesimal rotation (2.3) is contained in a tangent hyperplane of $I_n$ at a point $(X^i)$. Hence we may put a component of the vector $\xi_j^i X^j$ such that

$$\xi_j^i X^j = \eta^\alpha(u) X_{\alpha}^i.$$  

Differentiating the equation $\xi_j^i X^j X_i = 0$ with respect to $u^\alpha$, it becomes

$$X_{ia} \xi_j^i X^j + X_{i} \xi_j^i X^j_{a} = 0.$$  

Moreover if we covariantly differentiate (4.2) with respect to $u^\alpha$, we get

$$X_{ia} \xi_j^i X^j + X_{i} \xi_j^i X^j_{a} + X_{i} \xi_j^i X^j_{\beta} + X_{i} \xi_j^i X^j_{\alpha} = 0.$$  

However, substituting (3.5) and (3.6), in consequence of (2.10) and (4.2) it is easily seen that $X_{ia} \xi_j^i X^j + X_{i} \xi_j^i X^j_{a} = 0$ holds good. Therefore, we can reduce the above expression in the form

$$X_{ia} (\xi_j^i X^j)_{;\beta} + X_{ia} (\xi_j^i X^j)_{;\alpha} = 0.$$  

Making use of (4.1), we have from (4.3)

$$X_{ia} \gamma_{;\beta}^j X^i + X_{ia} \gamma_{;\alpha}^j X^i + X_{ia} \gamma_{a}^j X^i_{\beta} + X_{ia} \gamma_{a}^j X^i_{\alpha} = 0.$$  

On the other hand, by means of $g_{\alpha\beta}(u) = g_{ij}(X) X_a^i X^j_\beta$ and (3.5), it is easily verified that

$$X_{ia} X^i_\beta = g_{\alpha\beta}, \quad X_{ia} X^i_{\beta} = - A_{a\beta\gamma}.$$  

In consequence of these relations, we get from (4.4) $\eta_{\alpha;\beta} + \eta_{\beta;\alpha} = 2 \eta^\gamma A_{a\beta\gamma}$. Therefore we have

**Theorem 4.1.** If an infinitesimal point transformation $\overline{u}^\alpha = u^\alpha + \eta^\alpha(u) \delta t$ on $I_n$ coincides with a rotation in $M_{n+1}$, it must be satisfied that

$$\eta_{\alpha;\beta} + \eta_{\beta;\alpha} = 2 \eta^\gamma A_{a\beta\gamma}.$$  

When an infinitesimal point transformation on $I_n$ satisfies (4.5), we call it the *infinitesimal rotation on $I_n$.**
§ 5. Fundamental relations and formulas on Lie derivatives. In the following we give some fundamental formulas on Lie derivatives, which will be useful in the discussions of the present paper, and derive several relations for an infinitesimal rotation on $I_n$.

Denoting by $\mathfrak{T}_{\rho
u}^\lambda$ the Lie derivatives of an arbitrary tensor $T_{\mu\nu}^\lambda$ with respect to an infinitesimal transformation $\overline{u}^\alpha=u^\alpha+\eta^\alpha(u)\delta t$, it is given by the form

$$\mathfrak{T}_{\rho
u}^\lambda=T_{\mu\nu,\alpha}^\lambda\eta^\alpha-T_{\mu\nu}^\alpha\eta_{,\alpha}^\lambda+T_{\alpha
u}^\lambda\eta_{,\mu}^\alpha+T_{\rho\alpha}^\lambda\eta_{,\nu}^\alpha.$$ 

In general, we have

$$\mathfrak{T}[\rho^\alpha r]=\frac{1}{2}g^{\alpha\delta}[\mathfrak{T}g_{\delta\beta},_{\gamma}+(\mathfrak{T}g_{\delta\gamma}),_{\beta}-(\mathfrak{T}g_{\beta\gamma}),_{\delta}],$$

$$\mathfrak{T}[\beta\alpha r]=\eta_{,\beta}^\alpha-\mathfrak{T}[\beta\alpha r],$$

$$\mathfrak{T}[\delta^\alpha]=\mathfrak{T}[\beta\gamma r].$$

In consequence of Theorem 4.1, making use of the expression by Lie derivatives, an infinitesimal rotation on $I_n$ is characterized by the condition

$$\mathfrak{T}g_{\alpha\beta}=\eta_{,\alpha}^\gamma+\eta_{,\beta}^\alpha=2\eta^\gamma A_{\alpha\beta\gamma}.$$ 

Also, from (5.5) we get for an infinitesimal rotation on $I_n$

$$\mathfrak{T}g^{\alpha\beta}=-2\eta^\gamma A_{\alpha\beta\gamma},$$

and substituting (5.5) into (5.2) we have

$$\mathfrak{T}[\rho^\alpha r]=A_{,\rho}^\alpha\eta^\gamma+\eta_{,\rho}^\gamma(\delta_{,\gamma}^\alpha A_{\rho\delta\gamma}+\delta_{,\gamma}^\delta A_{\rho\delta}^{,\alpha}-g^{\alpha\delta}A_{\rho\delta\gamma}).$$

§ 6. Special case. When an indicatrix admits an intransitive group of rotations, we can derive some properties of the indicatrix in connection with structures of the group. In the following, as an example we shall consider the special 2-dimensional indicatrix $I_2$ in $M_3$, and derive its properties by means of the group structures.

For convenience’ sake, let us denote coordinates of a point in $M_3$ by $(x, y, z)$ in stead of $(x^1, x^2, x^3)$. If the finite equations of a centro-affine transformation in $M_3$ are given by

$$\begin{align*}
\bar{x}&=a_{11}x+a_{12}y+a_{13}z \\
\bar{y}&=a_{21}x+a_{22}y+a_{23}z \\
\bar{z}&=a_{31}x+a_{32}y+a_{33}z
\end{align*}$$

$$\text{det. }|a_{ij}|\neq 0,$$

all transformations of the type (6.1) form a 9-parameter Lie group $G_9$ and its symbols are given by
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$xf_x, yf_x, zf_x, \quad xf_y, yf_y, zf_y,$

$xf_z, yf_z, zf_z \quad (where \quad f_x \equiv \frac{\partial f}{\partial x}, \quad f_y \equiv \frac{\partial f}{\partial y}, \quad f_z \equiv \frac{\partial f}{\partial z}).$

Now, we shall suppose that an indicatrix $I_2$ is a revolutionary surface and equation of it has a form

$$F(x^2+y^2, z) = 1.$$  

(6.2)

Since we have from (6.2)

$$2F_x x dx + 2F_y y dy + F_z dz = 0 \quad (where \quad v = x^2+y^2),$$

the indicatrix $I_2$ admits a transformation determined by a generating vector with component $(y, -x, 0)$, namely admits a one-parameter group of rotations with the symbol $Xf = yf_x - xf_y$, which is one of subgroups contained in the above $G_9$. In this case, if we denote by $P(0, 0, z_0)$ and $Q(0, 0, -z_0)$ two points determined by intersection of $I_2$ and $z$-axis, then $P$ and $Q$ are fixed points of rotations.

On the other hand, except fixed points $P$ and $Q$, we may represent $I_2$ by three equations involving two parameters $u^1$ and $u^2$ such that

$$x = f(u^2) \cos u^1, \quad y = f(u^2) \sin u^1, \quad z = u^2,$$

where we put $x^2+y^2 = v(z) = f^2(z)$ and $u^1$ denotes angle between radius vector $(x, y, 0)$ and $x$-axis. Then we have

$$X_1^1 = \frac{\partial x}{\partial u^1} = -y, \quad X_1^2 = \frac{\partial y}{\partial u^1} = -x, \quad X_1^3 = \frac{\partial z}{\partial u^1} = 0,$$

$$X_2^1 = \frac{\partial x}{\partial u^2} = f' \cos u^1, \quad X_2^2 = \frac{\partial y}{\partial u^2} = f' \sin u^1, \quad X_2^3 = \frac{\partial z}{\partial u^2} = 1,$$

(6.3)

where $f' = \frac{df}{du^2}$.

Putting $\frac{1}{2} F^2(x^2+y^2, z) = L(x^2+y^2, z)$ and if we denote by $g_{\overline{i}\overline{j}}$ the components of fundamental metric tensor in $M_3$, we have

$$g_{11}^{11} = L_{xx} = 2L_v, \quad g_{11}^{22} = L_{yy} = 4x^2L_{vv}, \quad g_{11}^{33} = L_{zz} = 2xL_{vz},$$

$g_{22}^{11} = L_{xy} = 4xyL_{vv}, \quad g_{22}^{22} = L_{yy} = 2yL_{vz}$,

(6.4)

$$g_{33}^{33} = L_{zz}.$$

Also, from the definition $A_{\overline{i}\overline{j}\overline{k}} = \frac{1}{2} \frac{\partial g_{\overline{i}\overline{j}}}{\partial x^\overline{k}}$ it follows that

$$A_{\overline{1}11} = 6xL_{vo} + 4x^2L_{voo}, \quad A_{\overline{1}12} = 2yL_{vo} + 4x^2yL_{voo},$$

$$A_{\overline{1}13} = L_{vo} + 4x^2L_{voo}, \quad A_{\overline{1}22} = 2yL_{vo} + 4y^2L_{vvo},$$

$$A_{\overline{1}23} = 2yL_{vo} + 4y^2L_{voo}, \quad A_{\overline{1}33} = xL_{vzz},$$

$$A_{\overline{2}11} = 6yL_{vo} + 4y^2L_{voo}, \quad A_{\overline{2}12} = 2yL_{vo} + 4y^2L_{voo},$$

$$A_{\overline{2}22} = 2yL_{vo} + 4y^2L_{voo}, \quad A_{\overline{2}23} = 2yL_{vo} + 4y^2L_{voo},$$

$$A_{\overline{2}33} = xL_{vzz}, \quad A_{\overline{3}33} = yL_{vzz}, \quad A_{\overline{3}33} = \frac{1}{2} L_{vzz}.$$

(6.5)
Making use of (4.3), (4.4) and (4.5), we can obtain induced components $g_{a\beta}$ and $A_{a\beta\gamma}$ $(\alpha, \beta, \gamma=1, 2)$ of $g_{\overline{i}\overline{j}}$ and $A_{\overline{i}\overline{j}\overline{k}}$ respectively with respect to the reference system (6.3). After direct calculations we find that

\[ g_{12} = g_{\overline{i}\overline{j}} X_{1}^{\overline{i}} X_{1}^{\overline{j}} = 0, \quad A_{111} = A_{\overline{i}\overline{j}\overline{k}} X_{1}^{\overline{i}} X_{1}^{\overline{j}} X_{1}^{\overline{k}} = 0, \quad A_{122} = A_{\overline{i}\overline{j}\overline{k}} X_{1}^{\overline{i}} X_{2}^{\overline{j}} X_{2}^{\overline{k}} = 0. \]

As component of a generating vector of one-parameter group with symbol $Xf = y f_x - x f_y$ is $(y, -x, 0)$, denoting by $(\eta^1, \eta^2)$ its induced component with respect to the reference system (6.3), it follows that $y = \eta^1 X_1^\overline{3} + \eta^2 X_2^\overline{3}$, $-x = \eta^1 X_1^\overline{3} + \eta^2 X_2^\overline{3}$, $0 = \eta^1 X_1^\overline{3} + \eta^2 X_2^\overline{3}$. Therefore, substituting (6.3) into the above relations, we find that $\eta^\gamma = -\delta^\gamma_1$ holds good except at fixed points $P$ and $Q$.

Since $\eta^\gamma$ generates an infinitesimal rotation on $I_2$, in consequence of (4.5), it should be satisfied that $\eta_{\alpha;\beta} + \eta_{\beta;\alpha} = 2\eta^\gamma A_{\alpha\beta\gamma}$. However this last relation can be rewritten as follows:

\[ \eta^\gamma \frac{\partial g_{a\beta}}{\partial u^\gamma} + g_{\alpha\gamma} \frac{\partial \eta^\gamma}{\partial u^\beta} + g_{\beta\gamma} \frac{\partial \eta^\gamma}{\partial u^\alpha} = 2\eta^\gamma A_{a\beta\gamma} \quad (\alpha, \beta, \gamma=1, 2). \]

Substituting $\eta^\gamma = -\delta^\gamma_1$ into (6.7) it follows that $\partial g_{a\beta}/\partial u^1 = 2A_{a\beta 1}$. Then, in consequence of (6.6) we find that $g_{11}$ and $g_{22}$ do not contain a variable $u^1$. This shows us that in our example an infinitesimal rotation on $I_2$ coincides with a motion with respect to the metric in $I_2$ [8].

**Theorem 6.1.** In a 3-dimensional Minkowski space, if $I_2$ is a rotational surface, an infinitesimal rotation on $I_2$ coincides with a motion with respect to the induced Riemannian metric on $I_2$, and intersecting points on $I_2$ with its axis of rotation are fixed points of the transformation.

Moreover, as $g_{12} = 0$ it should be satisfied that $A_{112} = 0$. Therefore, by means of this relation and (6.6) we find that $S_{1212} = 0$ holds good at every point except at $P$ and $Q$.

In the followings, we shall study about properties of groups of infinitesimal rotations on $I_n$ under assumptions that $I_n$ has no singular point.

**§ 7. The determination of groups of infinitesimal rotations on $I_n$.**

We shall consider that under what conditions the equation

\[ \mathfrak{L} g_{a\beta} = \eta_{a;\beta} + \eta_{\beta;a} = 2\eta^\gamma A_{a\beta\gamma} \]

admits one or more solutions.

By means of (5.3) and (5.6), it follows that
On Groups of Rotations in Minkowski Space

(7.2) \[ \eta_{\beta;\gamma}^\alpha = \eta^\delta (A_{\beta\gamma;\delta}^\alpha + R_{\beta\gamma\delta}^\alpha) + \eta_{;\delta}^\alpha (\delta^\beta_\lambda A_{\alpha\beta\gamma}^\lambda + \delta^\alpha_\beta A_{\delta\gamma\lambda}^\lambda - g^{\alpha\lambda} A_{\beta\gamma\lambda}) \]

On the other hand, by means of the definition of covariant differential we have

(7.3) \[ \frac{\partial \eta^\alpha}{\partial u^\delta} = -\gamma^\delta \{s_\beta\} + \gamma_{;\beta}^\alpha, \]

(7.4) \[ \frac{\partial \eta_{;\beta}^\alpha}{\partial u^\gamma} = -\gamma_{;\beta}^\gamma \{s_\gamma\} + \eta_{;\delta}^\alpha \{\beta\delta\} + \gamma_{;\beta}^\alpha. \]

Substituting (7.2) into the last term in right hand side of the second equation, we can see that both \(\partial \eta^\alpha/\partial u^\delta\) and \(\partial \eta_{;\beta}^\alpha/\partial u^\gamma\) are expressed by linear forms with respect to \(\eta^\alpha\) and \(\eta_{;\beta}^\alpha\), and do not contain higher order derivatives of these unknown functions. In consequence of the above observations we have

**Theorem 7.1.** In order that a Riemannian space \(I_n\) admits an infinitesimal rotation on \(I_n\), it is necessary and sufficient that the system of linear partial equations

(7.5) \[ \frac{\partial \eta^\alpha}{\partial u^\delta} = -\gamma^\delta \{s_\beta\} + \gamma_{;\beta}^\alpha \]

(7.6) \[ \frac{\partial \eta_{;\beta}^\alpha}{\partial u^\gamma} = \eta^\delta (A_{\beta\gamma;\delta}^\alpha + R_{\beta\gamma\delta}^\alpha) + \gamma_{;\delta}^\alpha (\delta^\beta_\lambda A_{\alpha\beta\gamma}^\lambda + \delta^\alpha_\beta A_{\delta\gamma\lambda}^\lambda - g^{\alpha\lambda} A_{\beta\gamma\lambda}) \]

admits solutions \(\eta^\alpha\) and \(\eta_{;\beta}^\alpha\) under the condition

(7.7) \[ \eta_{\alpha;\beta} + \eta_{\beta;\alpha} = 2\eta^\gamma A_{\alpha\beta\gamma} \quad (\eta_{\alpha;\beta} = g_{\alpha\gamma} \eta_{;\beta}^\gamma). \]

Now, we shall seek the integrability conditions of the mixed system of partial differential equations (7.5)–(7.7). Differentiating (7.3) with respect to \(u^\gamma\) it follows that

\[ \frac{\partial^2 \eta^\alpha}{\partial u^\delta \partial u^\gamma} = -\frac{\partial \eta^\delta}{\partial u^\gamma} \{s_\beta\} - \gamma^\delta \frac{\partial \eta_{;\beta}^\alpha}{\partial u^\gamma} + \frac{\partial \eta_{;\beta}^\alpha}{\partial u^\gamma}. \]

If we substitute the relations (7.3) and (7.4) into the right hand side of the above expression, we obtain

\[ \frac{\partial^2 \eta^\alpha}{\partial u^{[\delta} \partial u^{\gamma]}} = 2 \left[ \eta^\gamma R_{\delta\gamma;\beta} + \gamma_{;\beta}^\gamma \{s_\gamma\} - \gamma_{;\beta}^\alpha \{s_\delta\} + \frac{\partial \eta_{;\beta}^\alpha}{\partial u^\gamma} - \frac{\partial \eta_{;\gamma}^\alpha}{\partial u^\delta} \right]. \]

According to the Ricci's identity, we may put \(\eta_{;\beta;\gamma} - \eta_{;\gamma;\beta} = -\eta^\delta R_{\delta\beta\gamma}\). Therefore \(\partial^2 \eta^\alpha/\partial u^{[\delta} \partial u^{\gamma]} = 0\) holds good identically. Next, we shall consider about (7.6).

Covariantly differentiating (7.2) with respect to \(u^\epsilon\), we obtain

6) We use the notation \([\ ]\) for the expression of skew-symmetric part such that \(T_{[\alpha\beta]} = \frac{1}{2}(T_{\alpha\beta} - T_{\beta\alpha}).\)
\[
\eta_{;\beta;\gamma;\epsilon}^\alpha = \eta^\delta (A_{\beta\gamma;\delta;\epsilon}^\alpha + R_{\beta\gamma;\delta;\epsilon}^\alpha) + \eta_{;\epsilon}^\delta (A_{\beta\gamma;\delta;\epsilon}^\alpha - g^{\alpha\beta} A_{\beta\gamma;\delta;\epsilon}) + \eta_{;\lambda}^\delta (\delta_{\gamma}^\lambda A_{\beta\delta;\epsilon}^\alpha + \delta_{\beta}^\lambda A_{\gamma\delta;\epsilon}^\alpha - g^{\alpha\lambda} A_{\beta\gamma\delta;\epsilon}) + \eta_{;\lambda;\epsilon}^\delta (A_{\beta\delta;\epsilon}^\alpha - \delta_{\beta}^\lambda A_{\delta\epsilon;\gamma}^\alpha - g^{\alpha\lambda} A_{\beta\gamma\delta;\epsilon}).
\]

In stead of \( \eta_{;\lambda;\epsilon}^\delta \) in the above equation, we substitute the term obtained from (7.2) by changing indices \( \alpha, \beta \) and \( \gamma \) by \( \delta, \lambda \) and \( \epsilon \) respectively. Then it follows that
\[
(7.8)
\eta_{;\beta;\gamma;\epsilon}^\alpha = \eta^\delta P_{\beta\gamma\delta\epsilon}^\alpha + \eta_{;\epsilon}^\delta Q_{\beta\gamma\delta\epsilon}^\alpha,
\]
where
\[
P_{\beta\gamma\delta\epsilon}^\alpha 
= A_{\beta\gamma;\delta;\epsilon}^\alpha + R_{\beta\gamma;\delta;\epsilon}^\alpha + A_{\beta\omega}(A_{\gamma\epsilon;\delta}^\omega + R_{\gamma\epsilon;\delta}^\omega) + A_{\omega\gamma}(A_{\beta\epsilon;\delta}^\omega + R_{\beta\epsilon;\delta}^\omega) - A_{\beta\gamma}(A_{\omega\delta;\epsilon}^\alpha - R_{\omega\delta;\epsilon}^\alpha),
\]
\[
Q_{\beta\gamma\delta\epsilon}^\alpha 
= \delta_{\gamma}^\lambda A_{\beta\delta;\epsilon}^\alpha + \delta_{\beta}^\lambda A_{\gamma\delta;\epsilon}^\alpha - g^{\alpha\lambda} A_{\beta\gamma\delta;\epsilon} + A_{\omega\gamma}^\alpha (A_{\beta\epsilon;\delta}^\omega + R_{\beta\epsilon;\delta}^\omega) - A_{\beta\gamma}^\omega (\delta_{\epsilon}^\lambda A_{\alpha\delta;\epsilon} + \delta_{\omega}^\lambda A_{\alpha\delta;\epsilon} - g^{\alpha\lambda} A_{\beta\gamma\delta;\epsilon}).
\]
By means of the Ricci’s identity we have
\[
(7.9)
\eta_{;\beta;\gamma;\epsilon}^\alpha - \eta_{;\beta;\gamma;\epsilon}^\alpha = \eta^\delta (P_{\beta\gamma\delta\epsilon}^\alpha - P_{\beta\epsilon\delta\gamma}^\alpha) + \eta_{;\epsilon}^\delta (Q_{\beta\gamma\delta\epsilon}^\alpha + Q_{\beta\epsilon\delta\gamma}^\alpha + \delta_{\beta}^\lambda R_{\delta\gamma\epsilon}^\alpha - \delta_{\lambda}^\alpha R_{\beta\gamma\epsilon}^\lambda).
\]
On the other hand, from (7.8) it follows that
\[
(7.10)
\eta_{;\beta;\gamma;\epsilon}^\alpha - \eta_{;\beta;\gamma;\epsilon}^\alpha = \eta^\delta (P_{\beta\gamma\delta\epsilon}^\alpha - P_{\beta\epsilon\delta\gamma}^\alpha) + \eta_{;\epsilon}^\delta (Q_{\beta\gamma\delta\epsilon}^\alpha + Q_{\beta\epsilon\delta\gamma}^\alpha + \delta_{\beta}^\lambda R_{\delta\gamma\epsilon}^\alpha - \delta_{\lambda}^\alpha R_{\beta\gamma\epsilon}^\lambda) = 0.
\]
In consequence of (7.9) and (7.10), the integrability conditions are written in the form
\[
(7.11)
\eta^\delta (P_{\beta\gamma\delta\epsilon}^\alpha - P_{\beta\epsilon\delta\gamma}^\alpha) + \eta_{;\epsilon}^\delta (Q_{\beta\gamma\delta\epsilon}^\alpha + Q_{\beta\epsilon\delta\gamma}^\alpha + \delta_{\beta}^\lambda R_{\delta\gamma\epsilon}^\alpha - \delta_{\lambda}^\alpha R_{\beta\gamma\epsilon}^\lambda) = 0.
\]
Making use of (3.8) and the Ricci’s identity we find that
\[
A_{\beta\gamma;\delta;\epsilon}^\alpha - A_{\beta\epsilon;\delta;\gamma}^\alpha = -A_{\beta\omega}^\alpha (R_{\omega\delta;\epsilon}^\alpha - S_{\omega\delta;\epsilon}^\alpha),
\]
and therefore, we obtain
\[
(7.12)
\eta^\delta (P_{\beta\gamma\delta\epsilon}^\alpha - P_{\beta\epsilon\delta\gamma}^\alpha) = \eta^\delta [-A_{\beta\omega}^\alpha (R_{\omega\delta;\epsilon}^\alpha + S_{\omega\delta;\epsilon}^\alpha) + A_{\omega\delta}^\alpha (R_{\beta\gamma;\delta;\epsilon}^\alpha - S_{\beta\gamma;\delta;\epsilon})] + 2A_{\omega\delta}^\alpha (R_{\beta\omega;\epsilon}^\alpha + S_{\beta\omega;\epsilon}^\alpha).
\]
\[
(7.13)
\eta_{;\epsilon}^\delta (Q_{\beta\gamma\delta\epsilon}^\alpha + Q_{\beta\epsilon\delta\gamma}^\alpha + \delta_{\beta}^\lambda R_{\delta\gamma\epsilon}^\alpha - \delta_{\lambda}^\alpha R_{\beta\gamma\epsilon}^\lambda) = \eta^\delta (2\delta_{\epsilon}^\alpha (R_{\beta\gamma;\delta;\epsilon}^\alpha - S_{\beta\gamma;\delta;\epsilon}) + \delta_{\beta}^\lambda (R_{\beta\gamma;\delta;\epsilon}^\alpha - S_{\beta\gamma;\delta;\epsilon}) - \delta_{\epsilon}^\alpha (R_{\beta;\gamma;\delta;\epsilon}^\alpha - S_{\beta;\gamma;\delta;\epsilon}) - 2g^{\alpha\delta} A_{\beta\omega}^\alpha (A_{\omega\gamma;\delta}^\alpha + A_{\omega\delta}^\alpha A_{\gamma\epsilon}^\delta - A_{\omega\delta}^\alpha A_{\gamma\epsilon}^\alpha).
\]
On the other hand, from the relation \( \eta_{;\alpha}^\delta g^{\alpha\delta} = 2\eta^\delta A_{\nu\delta \sigma} \), it follows that
\[
(7.14)
\eta_{;\epsilon}^\delta g^{\alpha\delta} = -\eta^\delta g^{\alpha\delta} + 2\eta^\delta A_{\nu\delta \sigma}.
\]
Substituting (7.14) into the last term in right hand side of (7.13), by means of the identity \( S_{\alpha\delta;\epsilon} = -S_{\beta;\gamma;\delta} = -S_{\alpha\beta;\delta} \), we get the relation
\[
(7.15)
\eta_{;\epsilon}^\delta (\delta_{\beta}^\lambda S_{\beta\gamma;\epsilon}^\alpha + g^{\alpha\delta} S_{\beta;\gamma;\delta}) = 2\eta^\delta A_{\nu\delta \sigma} S_{\alpha\beta;\delta}.
\]
In consequence of (7.12), (7.13) and (7.15), the integrability conditions (7.11) can be expressed as follows:

\begin{align}
\gamma^i & \left[ -A^\omega_{\beta\omega} R^\omega_{\beta\gamma\epsilon} + A^\omega_{\omega\beta} R^\omega_{\beta\gamma\epsilon} + (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) \delta_{;\beta} \\
& - 2(A^\omega_{\omega[\gamma} R^\omega_{\beta]\epsilon] \delta + A^\omega_{\beta[\epsilon} R^\omega_{\omega]\gamma] \delta} - A^\omega_{\beta]} S^\omega_{\omega\gamma\epsilon}) \right] \\
& + \gamma^i_j \{ \delta^j_{\beta} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) - \delta^j_{\epsilon} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) + 2A^\omega_{\omega[\epsilon} A^\omega_{\beta]} \delta \}
\end{align}

(7.16)

$$\gamma^i \left[ -A^\omega_{\beta\omega} R^\omega_{\beta\gamma\epsilon} + A^\omega_{\omega\beta} R^\omega_{\beta\gamma\epsilon} + (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) \delta_{;\beta} \\
- 2(A^\omega_{\omega[\gamma} R^\omega_{\beta]\epsilon] \delta + A^\omega_{\beta[\epsilon} R^\omega_{\omega]\gamma] \delta} - A^\omega_{\beta]} S^\omega_{\omega\gamma\epsilon}) \right] \\
+ \gamma^i_j \{ \delta^j_{\beta} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) - \delta^j_{\epsilon} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) + 2A^\omega_{\omega[\epsilon} A^\omega_{\beta]} \delta \} = 0.$$  

If we call our attention to the fact that in an n-dimensional Riemannian space $I_n$ the curvature tensor has the form (3.7), we obtain the following theorem:

**Theorem 7.2.** In an n-dimensional Riemannian space $I_n$, the system of linear partial differential equations for determination of groups of infinitesimal rotations on $I_n$ is completely integrable.

**Proof.** In the following we shall show that (7.16) holds good identically if the relation (3.7) is satisfied. By means of (3.7) and (7.7) it is easily seen that

\begin{align}
\gamma^i_j \{ \delta^j_{\beta} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) - \delta^j_{\epsilon} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) + 2\delta^j_{\beta} (R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) \}
= 2\gamma^i \{ \delta^j_{\beta} A^\omega_{\beta\gamma\epsilon} - \delta^j_{\epsilon} A^\omega_{\beta\gamma\epsilon} \}.
\end{align}

Also, from (3.7) we must have $(R^\omega_{\beta\gamma\epsilon} - S^\omega_{\beta\gamma\epsilon}) \delta_{;\beta} = 0$. Accordingly (7.16) can be rewritten as follows:

\begin{align}
\gamma^i \{ -A^\omega_{\beta\omega} R^\omega_{\beta\gamma\epsilon} + A^\omega_{\omega\beta} R^\omega_{\beta\gamma\epsilon} - 2(A^\omega_{\omega[\gamma} R^\omega_{\beta]\epsilon] \delta + A^\omega_{\beta[\epsilon} R^\omega_{\omega]\gamma] \delta} - A^\omega_{\beta]} S^\omega_{\omega\gamma\epsilon}) \}
\end{align}

(7.16')

$$\gamma^i \left[ -A^\omega_{\beta\omega} R^\omega_{\beta\gamma\epsilon} + A^\omega_{\omega\beta} R^\omega_{\beta\gamma\epsilon} - 2(A^\omega_{\omega[\gamma} R^\omega_{\beta]\epsilon] \delta + A^\omega_{\beta[\epsilon} R^\omega_{\omega]\gamma] \delta} - A^\omega_{\beta]} S^\omega_{\omega\gamma\epsilon}) \right] \\
+ \gamma^i_j \{ 2A^\omega_{\omega[\epsilon} A^\omega_{\beta]} \delta \} = 0.$$  

On the other hand, making use of (5.3), (5.4) and (5.7), after some complicated calculations we get

\begin{align}
\mathfrak{L} R^\omega_{\beta\gamma\epsilon} - \mathfrak{L} S^\omega_{\beta\gamma\epsilon} + \mathfrak{L} (2\delta^j_{\beta} A^\omega_{\epsilon\beta\gamma} - 2\delta^j_{\epsilon} A^\omega_{\beta\gamma\epsilon}) = 0.
\end{align}

(7.17)

Comparing (7.16') and (7.17), the integrability conditions may be reduced in the form

$$\mathfrak{L} R^\omega_{\beta\gamma\epsilon} - \mathfrak{L} S^\omega_{\beta\gamma\epsilon} + \mathfrak{L} (2\delta^j_{\beta} A^\omega_{\epsilon\beta\gamma} - 2\delta^j_{\epsilon} A^\omega_{\beta\gamma\epsilon}) = 0.$$  

However, since $\mathfrak{L} g_{\alpha\beta} = 2\gamma^j A_{\alpha\beta\gamma}$, it is readily seen that

$$\gamma^j (2\delta^j_{\beta} A_{\epsilon\beta\gamma} - 2\delta^j_{\epsilon} A_{\beta\gamma\epsilon}) = \mathfrak{L} (\delta^j g_{\beta\epsilon} - \delta^j g_{\beta\epsilon}).$$  

Therefore, finally we have the following form of the integrability conditions:
The above relation gives us the result of Theorem 7.2.

In consequence of Theorem 7.2 and the theory of linear partial differential equations, we can see that the general solution involves at most $\frac{1}{2}n(n+1)$ parameters, because the system of partial differential equations (7.5) and (7.6) with respect to $n+n^2$ unknown function $\gamma^a$ and $\gamma\beta^\alpha$, is completely integrable under $\frac{1}{2}n(n+1)$ conditions (7.7). Then we have

**Theorem 7.3.** The maximum order of groups of infinitesimal rotations on $I_n$ is equal to $\frac{1}{2}n(n+1)$.

§ 8. Properties of an infinitesimal rotation on $I_n$. In the following, we shall consider properties of an infinitesimal transformation $\bar{w}^a = u^a + \gamma^a(w)\delta t$, where $\gamma^a$ satisfies the relation

$$(8.1) \quad \gamma_{\alpha;\beta} + \gamma_{\beta;\alpha} = 2\gamma^\gamma A_{\alpha\beta\gamma} \quad (\gamma^a = g_{\alpha\beta}\gamma^\beta).$$

As a special case, if the vector $A^a$ generates an infinitesimal rotation on $I_n$, it should be satisfied that

$$(8.2) \quad A_{\alpha;\beta} + A_{\beta;\alpha} = 2A^\gamma A_{\alpha\beta\gamma}.$$ 

Multiplying (8.2) by $g^{a\beta}$ and summing for $\alpha$ and $\beta$, it follows that $A^\gamma = A^\gamma A_{\gamma}$. Since $I_n$ is a compact Riemannian space, if $I_n$ is an orientable manifold, by means of the theorem of Green, we find that

$$(8.3) \quad \int_{I_n} A^\gamma_{\alpha} d\sigma = \int_{I_n} A^\gamma A_{\alpha} d\sigma = 0.$$

In consequence of $A^\gamma A_{\gamma} = g_{\gamma} A^\gamma A^\gamma \geq 0$, (8.3) implies $A^\gamma A_{\gamma} = 0$. Therefore $A_{\gamma} = 0$ should be held at every point on $I_n$. This means that the considered Minkowski space $M_{n+1}$ is essentially a Euclidean space [9]. Thus we have

**Theorem 8.1.** In $I_n$ the generating vector $\gamma^a$ of an infinitesimal rotation does not coincide with the vector $A^a$, otherwise $M_{n+1}$ is essentially a Euclidean space and the infinitesimal transformation becomes the identity transformation.

Let us suppose that a vector $\rho \gamma^a$ generates an infinitesimal rotation on $I_n$. In order that a vector $\rho \gamma^a$, where $\rho$ is a scalar function, generates also an infinitesimal rotation on $I_n$, it is necessary and sufficient that we have

$$(8.4) \quad (\rho \gamma_{\alpha})_{;\beta} + (\rho \gamma_{\beta})_{;\alpha} = 2\rho \gamma^\gamma A_{\alpha\beta\gamma}.$$
However, since the vector $\eta_\alpha$ satisfies the relation (8.1), we have from (8.4)

$$\rho,_{\beta}\eta_\alpha + \rho,_{\alpha}\eta_\beta = 0 \quad \left( \rho,_{\alpha} = \frac{\partial \rho}{\partial u^{\alpha}} \right) \tag{8.5}$$

Replacing $\beta$ by $\gamma$ in (8.5), we have a similar relation

$$\rho,_{\gamma}\eta_\alpha + \rho,_{\alpha}\eta_\gamma = 0 \quad \tag{8.6}$$

Then, eliminating $\eta_\alpha$ from (8.5) and (8.6), we get

$$\rho,_{\alpha}(\rho,_{\gamma}\rho_{\beta} - \rho,_{\beta}\rho_{\gamma}) = 0 \quad \tag{8.7}$$

The relation (8.7) shows us that if we suppose that $\rho,_{\alpha} \not\equiv 0$, then $\rho,_{\gamma}\rho_{\beta} - \rho,_{\beta}\rho_{\gamma} = 0$ must be satisfied. However, in such a case, since we have $\rho,_{\gamma}\rho_{\beta} + \rho,_{\beta}\rho_{\gamma} = 0$, it follows that $\rho,_{\gamma}\rho_{\beta} = 0$. Therefore, from our assumption we should have $\eta_\beta = 0$. Accordingly, we must have $\rho,_{\alpha} = 0$. Then,

**Theorem 8.2.** Two infinitesimal rotations on $I_n$ cannot have the same trajectory.

Next, let us consider the case when the trajectory for an infinitesimal rotation on $I_n$ is geodesic of the Riemannian space $I_n$. Then we must have (8.1) and

$$\eta_{\alpha};_{\beta}\eta^\beta = \rho\eta_\alpha, \quad \tag{8.8}$$

where $\rho$ is a scalar function. Multiplying (8.1) by $\eta^\alpha \eta^\beta$ and summing for $\alpha$ and $\beta$, by means of (8.8) we get

$$\rho\eta_\alpha\eta^\beta = A_{\alpha\beta\gamma}\eta^\alpha\eta^\beta\eta^\gamma \quad \tag{8.9}$$

On the other hand, if we contract $\eta^\alpha$ to (8.1) and making use of (8.8) it follows that

$$\frac{1}{2}(\eta_{\alpha}\eta^\beta)_{;\beta}\eta^\beta + \rho\eta_\beta = 2A_{\alpha\beta\gamma}\eta^\alpha\eta^\beta\eta^\gamma. \quad \tag{8.10}$$

Moreover, making contraction by $\eta^\beta$, the above relation becomes

$$\frac{1}{2}(\eta_{\alpha}\eta^\beta)_{;\beta} + \rho\eta_\beta\eta^\beta = 2A_{\alpha\beta\gamma}\eta^\alpha\eta^\beta\eta^\gamma. \quad \tag{8.11}$$

Comparing (8.9) and (8.10), we must have $(\eta_{\alpha}\eta^\beta)_{;\beta}\eta^\beta = 2\rho(\eta_{\alpha}\eta^\beta)$, namely $\mathfrak{L}(g_{\lambda\nu}\eta^\lambda\eta^\nu) = 2\rho(g_{\lambda\nu}\eta^\lambda\eta^\nu)$. Consequently it follows that $\mathfrak{L}g_{\lambda\nu} = 2\rho g_{\lambda\nu}$. This implies that the infinitesimal rotation on $I_n$ is an infinitesimal conformal transformation.

**Theorem 8.3.** If the trajectory of an infinitesimal rotation on $I_n$ is a geodesic of the Riemannian space $I_n$, the transformation must be an infinitesimal conformal one.
Let $\eta_{(a)}^\alpha (a=1, 2, \cdots, r)$ be vectors of $r$ one-parameter groups of infinitesimal rotations on $I_n$. Then we have $\mathcal{L}_a g_{\alpha\beta} = 2\eta_{(a)}^\gamma A_{\alpha\beta\gamma}$ and from which it follows that
\[
\mathcal{L}_a g_{\alpha\beta} = 2\eta_{(a)}^\gamma A_{\alpha\beta\gamma},
\]
where $c^a$ are arbitrary constants.

If we introduce the notation $X_a f = \eta_{(a)}^{\alpha} \frac{\partial f}{\partial u^\alpha}$, it is a symbol of the infinitesimal transformation $\overline{u}^\alpha = u^a + \eta_{(a)}^{a}(u) \delta t$. In consequence of (8.11), we have the following

**Theorem 8.4.** If $X_a f$ are symbols of $r$ one-parameter groups of infinitesimal rotations on $I_n$, then $c^a X_a f$ is also a symbol of a one-parameter group of infinitesimal rotations on $I_n$, where $c^a$ are arbitrary constants.

If $X_a f$ are the generators of an $r$-parameter group, then the transformations of this group consist of the transformations of one-parameter groups generated by the infinitesimal transformation $c^a X_a f$ and of the products of such transformations [8]. Thus in consequence of Theorem 8.4, we obtain

**Theorem 8.5.** When each of $r$ generators of an $r$-parameter group $G_r$ of transformations is a generator of a one-parameter group of rotations on $I_n$, every transformation of the group $G_r$ is a rotation on $I_n$.

By virtue of the second fundamental theorem of Lie, if $r$ independent linear operator $X_a f$ constitute a complete system of order $r$, then the transformations of the group, generated by the infinitesimal transformations $c^a X_a f$ or products of such transformations, form an $r$-parameter group $G_r$ of transformations. Then making use of the result of Theorem 8.5 we obtain

**Theorem 8.6.** If $X_a f$ are $r$ generators of a complete set of one-parameter groups of infinitesimal rotations on $I_n$, then they are generators of an $r$-parameter group of infinitesimal rotations on $I_n$.

The properties of an infinitesimal rotation on $I_n$, when the transformation coincides with a motion or transformations of other special classes and also the structures of $r$-parameter groups of infinitesimal rotations on $I_n$ will be discussed more precisely in the next paper.

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