

3. Matrices related to f

Objektyp: **Chapter**

Zeitschrift: **L'Enseignement Mathématique**

Band (Jahr): **10 (1964)**

Heft 1-2: **L'ENSEIGNEMENT MATHÉMATIQUE**

PDF erstellt am: **26.04.2024**

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$f_c = f(c_1, \dots, c_n)$. Then

$$(x_1 - c_1 \dots x_n - c_n) \begin{bmatrix} \frac{\partial^2 f}{\partial c_1 \partial \bar{c}_1} & \dots & \frac{\partial^2 f}{\partial c_1 \partial \bar{c}_n} \left(\frac{\partial f}{\partial c_1} \right) \\ \vdots & & \vdots \\ \frac{\partial^2 f}{\partial c_n \partial \bar{c}_1} & & \frac{\partial^2 f}{\partial c_n \partial \bar{c}_n} \left(\frac{\partial f}{\partial c_n} \right) \\ \frac{\partial f}{\partial c_1} & & \frac{\partial f}{\partial c_n} & f_c \end{bmatrix} \begin{bmatrix} x_1 - c_1 \\ \vdots \\ x_n - c_n \\ 1 \end{bmatrix} = 0 \quad (2.1)$$

is called the tangent quadric of f at $(c_1, \dots, c_n)$. We shall study only the cases that at least one of the first or second derivatives is not zero. It is clear that the tangent plane of (2.1) at $(c_1, \dots, c_n)$ is the same as the tangent plane of $f = 0$ at this point.

Let the matrix of (2.1) be A , $\xi = (x_1 - c_1 \dots x_n - c_n)$, and $\eta = (0 \dots 0 \ 1)$. Then by section 8 of [1]

$$\xi A \eta^* = 0 \quad (2.2)$$

is the tangent plane of (2.1) at $(c_1, \dots, c_n)$. Here η^* is the conjugate transpose of η .

We easily see that (2.2) can be written as

$$\sum_{i=1}^n \frac{\partial f}{\partial c_i} (x_i - c_i) = 0. \quad (2.3)$$

3. MATRICES RELATED TO f

Besides A there are other matrices of some interest. We denote the matrix of the quadratic form of (2.1) by Q . The projection on the normal and tangent plane are of some interest. We denote the projection on the normal by P , and clearly $I - P$ is the projection on the tangent plane where I is the identity matrix. It is easy to see that $P = (P_{ij})$, where

$$P_{ij} = \frac{\left(\frac{\partial f}{\partial x_i}\right) \frac{\partial f}{\partial x_j}}{\sum \left|\frac{\partial f}{\partial x_i}\right|^2}.$$

This is proved by considering the inner product of a vector $\xi = (x_1, \dots, x_n)$ and a unit vector on

$$\left(\frac{\partial f}{\partial x_1}, \dots, \frac{\partial f}{\partial x_n}\right).$$

3. QUADRIC CURVATURE

If (2.1) becomes of the form

$$[\sum a_i (x_i - c_i)] [\sum \bar{a}_i (\bar{x}_i - \bar{c}_i)] = 0,$$

then $f(x_1, \dots, x_n)$ is called doubly flat at $(c_1, \dots, c_n)$. Suppose (2.1) does not have this form. Then by sec 6 of [1] centers $(x_1, \dots, x_n)$ of (2.1) may be obtained by

$$\xi Q = - \left(\frac{\partial f}{\partial \xi}\right), \quad (3.1)$$

where the row matrix ξ is:

$$\xi = (x_1 - c_1 \dots x_n - c_n), \text{ and } \frac{\partial f}{\partial \xi} = \left(\frac{\partial f}{\partial c_1} \dots \frac{\partial f}{\partial c_n}\right).$$

The equation (3.1) is a system of n linear equations in n unknowns.

The following cases may occur:

I. Let Q be non-singular. Then the quadric has a unique center which is called the center of quadric curvature of $f(x_1, \dots, x_n)$ at $\gamma = (c_1, \dots, c_n)$. Let

$$\xi = - \left(\frac{\partial f}{\partial \xi}\right) Q^{-1}.$$

Then the center is the point defined by $\xi - \gamma$.

II. Let the rank of Q be k , and centers exist. Then these centers are solutions of

$$\xi_k = \xi E = - \left(\frac{\partial f}{\partial \xi} \right) EQ^{-1}, \quad (3.2)$$

where Q^{-1} is the reciprocal of Q , see [2]. That is, if E is the projection on the range of Q , then

$$Q^{-1} Q = QQ^{-1} = E.$$

Here we choose the center of quadric curvatures at a point of (3.2) so that, it is at the shortest distance from γ .

III. When the rank of Q is k and the quadric does not have centers, then we say that f does not have a center of quadric curvature.

4. DIRECTION OF QUADRIC CURVATURE

In part I and II of section 3 we respectively call the vectors ξ and ξ_k the directions of quadric curvature of f at $(c_1, \dots, c_n)$. In III of section 3, we define the direction of quadric curvature to be a vector δ which satisfies

$$\delta = \delta E = - \left(\frac{\partial f}{\partial \xi} \right) EQ^{-1},$$

where E is the projection described in section 3.

5. VERTEX POINTS

Let at the point $\gamma = (c_1, \dots, c_n)$ of f the direction of quadric curvature be the same as the normal to $f = 0$. Then γ is called a vertex point of the function f .

Theorem: A necessary and sufficient condition for a point to be a vertex point of the function f is that at that point

$$PQ = QP,$$

where P and Q are the matrices described in section 3.