

Variational problems
for the conformality of maps
and
for pullback metrics

山口大学理学研究科 中内伸光 (Nobumitsu Nakauchi)
Graduate School of Science and Engineering
Yamaguchi University

§0. Introduction

There exists a fundamental question:

Question What maps are closest to conformal ones?

We give a variational approach to this question. We consider the functional

$$\Phi(f) = \int_M \|T_f\|^2 dv_g,$$

where T_f is a covariant symmetric tensor such that

$$T_f = 0 \iff f \text{ is a weakly conformal map.}$$

In this note we give a brief summary of results for this functional.

§1. A variational problem for the conformality of maps

We use the following notations throughout this note:

Notations

$\left. \begin{matrix} (M, g) \\ (N, h) \end{matrix} \right\}$	: compact Riemannian manifolds without boundary.
m	: the dimension of M
f	: a smooth map from M into N .
X, Y	: vector fields on M .
e_i	: a local orthonormal frame on M .
f^*h	: the pullback of the metric h by the map f , i.e., $(f^*h)(X, Y) = h(df(X), df(Y))$

We first recall notions of the conformality of maps:

Conformal and Weakly conformal

(1) A smooth map f is **weakly conformal** if there exists a **non-negative** function φ on M such that

$$(*) \quad f^*h = \varphi g.$$

(2) A smooth map f is **conformal** if there exists a **positive** function φ on M satisfying (*).

Note that f is weakly conformal if and only if it is conformal at x or $(df)_x = 0$ for any $x \in M$ ¹.

¹ A map f is called conformal at $x \in M$ if it satisfies (*) at x .

We give a tensor of the conformality. Let $\|df\|$ denote the energy density of f in the theory of harmonic maps, i.e.,

$$\|df\|^2 = \sum_{i=1}^m h(df(e_i), df(e_i)).$$

We consider the following covariant symmetric tensor:

Tensor T_f

$$T_f \stackrel{\text{def}}{=} f^*h - \frac{1}{m}\|df\|^2 g,$$

i.e.,

$$T_f(X, Y) \stackrel{\text{def}}{=} h(df(X), df(Y)) - \frac{1}{m}\|df\|^2 g(X, Y).$$

Remark. In the case of $m = 2$, the tensor T_f is equal to the stress energy tensor

$$S_f = f^*h - \frac{1}{2}\|df\|^2 g$$

for harmonic maps. (See Eells and Lemaire [2], p.392.)

We can verify the following basic properties for the tensor T_f :

— Properties of tensor T_f —

Lemma T.

- (1) T_f is symmetric, i.e., $T_f(X, Y) = T_f(Y, X)$.
- (2) f is weakly conformal if and only if $T_f = 0$.
- (3) $\|T_f\|^2 = \|f^*h\|^2 - \frac{1}{m}\|df\|^4$.
- (4) T_f is trace-free, i.e.,

$$\text{Tr}_g T_f = \sum_{i,j=1}^m g(e_i, e_j) T_f(e_i, e_j) = 0.$$

- (5) The trace of T_f with respect to the pullback f^*h is equal to the norm of T_f , i.e.,

$$\text{Tr}_{f^*h} T_f = \sum_{i,j=1}^m (f^*h)(e_i, e_j) T_f(e_i, e_j) = \|T_f\|^2.$$

We are concerned with the following functional:

— Functional $\Phi(f)$ —

$$\Phi(f) = \int_M \|T_f\|^2 dv_g.$$

This functional $\Phi(f)$ gives a quantity of the conformality of maps f . Note that if f is a conformal map, then $\Phi(f)$ vanishes. In this note we give the following results ([5], [4], [6], [3]):

1. First variation formula
2. Second variation formula
3. Weak conformality for maps from or into spheres
4. Quasi-monotonicity formula
5. Bochner type formula
6. Existence of minimizers in 3-homotopy class
7. Other variational problem

§2. First variation formula

In this section we give the first variation formula for the functional $\Phi(f)$. We first define the following “ $f^{-1}TN$ -valued” 1-form ξ_f ². The 1-form ξ_f plays an important role in our arguments.

1-form ξ_f

$$\begin{aligned}\xi_f(X) &= \sum_j T_f(X, e_j) df(e_j) \\ &= \sum_j h(df(X), df(e_j)) df(e_j) - \frac{1}{m} \|df\|^2 df(X).\end{aligned}$$

Take any smooth deformation F of f , i.e., any smooth map

$$F : (-\varepsilon, \varepsilon) \times M \longrightarrow N \text{ s.t. } F(0, x) = f(x).$$

Let $f_t(x) = F(t, x)$, and we often say a deformation $f_t(x)$ instead of

² Though I want to use the notation τ_f instead of ξ_f , it is confused with the notation of the tension field in the theory of harmonic maps.

a deformation $F(t, x)$. Let

$$X = dF\left(\frac{\partial}{\partial t}\right)\Big|_{t=0}$$

denote the variation vector fields of the deformation F . Then we have the following first variation formula.

First variation formula

$$\frac{d\Phi(f_t)}{dt}\Big|_{t=0} = -4 \int_M h(X, \operatorname{div}_g \xi_f) dv_g.$$

Here dv_g denotes the volume form on M , and $\operatorname{div}_g \xi_f$ denotes the divergence of ξ_f , i.e., $\operatorname{div}_g \xi_f = \sum_{i=1}^m (\nabla_{e_i} \xi_f)(e_i)$.

We give here the notion of *C-stationary maps*.

C-stationary map

We call a smooth map f **C-stationary** if

$$\frac{d\Phi(f_t)}{dt}\Big|_{t=0} = 0$$

for any smooth deformation f_t of f .

By the first variation formula, a smooth map f is *C-stationary* if and only if it satisfies the following equation:

Euler-Lagrange equation

$$\operatorname{div}_g \xi_f = 0.$$

§3. Second variation formula

In this section we give the second variation formula for the functional $\Phi(f)$. Take any smooth deformation F of f with two parameters, i.e., any smooth map

$$F : (-\varepsilon, \varepsilon) \times (-\delta, \delta) \times M \longrightarrow N \text{ s.t. } F(0, 0, x) = f(x).$$

Let $f_{s,t}(x) = F(s, t, x)$, and we often say a deformation $f_{s,t}(x)$ instead of a deformation $F(s, t, x)$. Let

$$X = dF\left(\frac{\partial}{\partial s}\right)\Big|_{s,t=0}, \quad Y = dF\left(\frac{\partial}{\partial t}\right)\Big|_{s,t=0}$$

denote the variation vector fields of the deformation F . Then we have the following second variation formula.

Second variation formula

$$\begin{aligned} \frac{1}{4} \frac{\partial^2 \Phi(f_{s,t})}{\partial s \partial t} \Big|_{s,t=0} &= \int_M h(\text{Hess}_F\left(\frac{\partial}{\partial s}, \frac{\partial}{\partial t}\right), \text{div}_g \xi_f) dv_g \\ &+ \int_M \sum_{i,j} h(\nabla_{e_i} X, \nabla_{e_j} Y) T_f(e_i, e_j) dv_g \\ &+ \int_M \sum_{i,j} h(\nabla_{e_i} X, df(e_j)) h(\nabla_{e_i} Y, df(e_j)) dv_g \\ &+ \int_M \sum_{i,j} h(\nabla_{e_i} X, df(e_j)) h(df(e_i), \nabla_{e_j} Y) dv_g \\ &- \frac{2}{m} \int_M \sum_i h(\nabla_{e_i} X, df(e_i)) \sum_j h(\nabla_{e_j} Y, df(e_j)) dv_g \\ &- \int_M \sum_{i,j} h({}^N R(df(e_i), X) Y, df(e_j)) T_f(e_i, e_j) dv_g. \end{aligned}$$

Here Hess_f denotes the Hessian of f , i.e., $\text{Hess}_f(Z, W) = (\nabla_Z df)(W) = (\nabla_W df)(Z)$.

Remark. Note that the first term in the right hand side vanishes if f is a C-stationary map.

Remark. The last term of the right hand side is equal to

$$- \int_M \sum_i h({}^N R(df(e_i), X) Y, \xi_f(e_i)) dv_g.$$

§4. Weak conformality for maps from or into spheres

A C-stationary map f is called to be **stable** if the second variation at f is non-negative. We give two results for the weak conformality of stable C-stationary maps. (See Kawai-Nakauchi [4].)

Weak conformailty

Let f be a stable C-stationary map from the standard sphere S^m into a Riemannian manifold N . If $m \geq 5$, then f is a weakly conformal map.

Weak conformailty

Let f be a stable C-stationary map from a Riemannian manifold M into the standard sphere S^n . If $n \geq 5$, then f is a weakly conformal map.

The above results can be regarded as a type of Liouville theorems since the trivial case for the functional Φ is that of not constant maps,

but weakly conformal maps. On the other hand, stable C-stationary maps are not weakly conformal in general. We see the following fact.

Existence of non-conformal stable C-stationary maps

There exists a stable C-stationary maps which is not weakly conformal.

This fact follows from a simple example. Let us define a map

$$\begin{array}{ccc} f : S^1 \times S^1 \times \dots \times S^1 & \longrightarrow & S^1(r) \times S^1 \times \dots \times S^1 \\ \cup & & \cup \\ (x^1, x^2, \dots, x^m) & \longmapsto & (rx^1, x^2, \dots, x^m) \end{array}$$

where S^1 (resp. $S^1(r)$) denotes the sphere of dimension 1 with radius 1 (resp. r) centered at the origin of $\mathbb{R}^2$. Obviously f is not weakly conformal if $r \neq 1$. By simple calculations, we can verify that f is a C-stationary map, and that f is stable if r is sufficiently close to 1.

§5. Quasi-monotonicity formula

In this section we prove a kind of the monotonicity formula for C-stationary maps. We give this formula under the following weak condition.

C-stationary w.r.t. diffeomorphisms

We call a map f **C-stationary with respect to diffeomorphisms on M** if

$$\left. \frac{d}{dt} \Phi(f \circ \varphi_t) \right|_{t=0} = 0$$

for any 1-parameter family φ_t of diffeomorphisms on M .

Note that the above notion of C-stationary maps is weaker than the previous one of C-stationary maps, since $f_t(x) = f \circ \varphi_t(x)$ is a deformation in the former notion.

Let $B_\rho(x_0)$ be the open ball of a radius ρ with a center $x_0 \in M$. Then we have the following formula:

Quasi-monotonicity formula

For any *C-stationary map* f with respect to diffeomorphisms, we have

$$\frac{d}{d\rho} \left\{ e^{C\rho} \rho^{4-m} \int_{B_\rho(x_0)} \|T_f\|^2 dv_g \right\} \geq 4e^{C\rho} \rho^{4-m} \left(\varphi'(\rho) + \frac{C}{4}\varphi(\rho) \right)$$

where

$$\varphi(\rho) = \int_{B_\rho(x_0)} h(df\left(\frac{\partial}{\partial r}\right), \xi_f\left(\frac{\partial}{\partial r}\right)) dv_g.$$

Remark. If $\varphi(\rho)$ satisfies the condition $\varphi'(\rho) + \frac{C}{4}\varphi(\rho) \geq 0$, then $e^{C\rho} \rho^{4-m} \int_{B_\rho(x_0)} \|T_f\|^2 dv_g$ is monotone non-decreasing. We cannot expect such a monotonicity in general, since T_f is indefinite.

§6. Bochner type formula

Bochner formulas are basic tools for various arguments in geometry. For the norm of T_f , we have the following Bochner type formula:

Bochner type formula

$$\begin{aligned}
\frac{1}{4} \Delta \|T_f\|^2 &= \operatorname{div}_g \alpha_f - h(\tau_f, \operatorname{div}_g \xi_f) + \frac{1}{2} \|\nabla T_f\|^2 \\
&+ \sum_{i,j,k} h((\nabla_{e_k} df)(e_i), (\nabla_{e_k} df)(e_j)) T_f(e_i, e_j) \\
&+ \sum_{i,j} h(df(\sum_k^M R(e_i, e_k) e_k), df(e_j)) T_f(e_i, e_j) \\
&- \sum_{i,j,k} h({}^N R(df(e_i), df(e_k)) df(e_k), df(e_j)) T_f(e_i, e_j)
\end{aligned}$$

where

$$\alpha_f(X) = h(\xi_f(X), \tau_f).$$

Here $\tau_f = \operatorname{tr}(\nabla df) = \sum_j (\nabla_{e_j} df)(e_j)$ is the tension field of f in the theory of harmonic maps. (See Eells and Lemaire [1], p.9.)

Remark. The first term in the right hand side is of divergence form, and hence the integral of it over M vanishes.

Remark. The second term in the right hand side vanishes if f is a C-stationary map.

Remark. The last two terms of the right hand side are equal to

$$+ \sum_{i,k} h(df(\sum_k^M R(e_i, e_k) e_k), \xi_f(e_i))$$

and

$$- \sum_{i,k} h({}^N R(df(e_i), df(e_k)) df(e_k), \xi_f(e_i))$$

respectively.

§7. Existence of local minimizers

In this section we utilize the notion of 3-homotopy in the Sobolev spaces, which is given by White, and consider a variational problem of minimizing the functional $\Phi(f)$ in each 3-homotopy class. For any two maps f_1 and f_2 from M into N , these maps are **k -homotopic** ($k \in \mathbb{N}$) if they are homotopic to each other on k -dimensional skeletons of a triangulation on M .

By Nash's isometric embedding, we may assume that N is a submanifold of a Euclidean space $\mathbb{R}^q$. Let

$$L^{1,p}(M, N) = \{ f \in L^{1,p}(M, \mathbb{R}^q) \mid f(x) \in N \text{ a.e.} \},$$

where $L^{1,p}(M, \mathbb{R}^q)$ denotes the Sobolev space of $\mathbb{R}^q$ -valued L^p -functions on M such that their derivatives are in L^p . Then White proved that the notion of the $[p-1]$ -homotopy is compatible with the Sobolev space $L^{1,p}(M, N)$, where $[\]$ denotes the Gauss symbol, i.e., $[r]$ is the maximum integer less than or equal to r . We recall the following results by White [8]. (See also White [7].)

Known results

- (1) The $[p-1]$ -homotopy is well-defined for any map $f \in L^{1,p}(M, N)$.
- (2) If f_j converges weakly to f_∞ in $L^{1,p}(M, N)$, then f_j and f_∞ are $[p-1]$ -homotopic for sufficient large j .

The functional $\Phi(f)$ is defined on $L^{1,4}(M, N)$, in which the 3-homotopy is well-defined. Then for any given continuous map f_0 from M into N , we want to minimize the functional $\Phi(f)$ in the following class:

$$\mathcal{F} = \{ f \in L^{1,4}(M, N) \mid f \text{ is 3-homotopic to } f_0 \text{ and } \|f\|_{L^{1,4}(M, N)} \leq C_0 \},$$

where C_0 is a given positive constant. We may assume that the space

$\mathcal{F}$ is not empty for sufficiently large C_0 .

Existence of minimizers

There exists a minimizer of the functional $\Phi(f)$ in $\mathcal{F}$.

If a 3-homotopy class contains a conformal map, then the conformal map is a minimizer. Minimizers are expected to be *closest* to conformal maps, even if its 3-homotopy class does not contain any conformal map.

Remark. When M is 4-dimensional and $\pi_4(N) = 0$, any *continuous* minimizer is (freely) homotopic to f_0 in the ordinary sense.

§8. Other variational problem

By Lemma T (3), we see

$$\|T_f\|^2 = \|f^*h\|^2 - \frac{1}{m}\|df\|^4.$$

$\uparrow$

the norm of
the pullback metric

$\uparrow$

the energy density
of 4-harmonic maps

Then we consider the following functional for pullback metrics.

Functional $F(f)$

$$F(f) = \int_M \|f^*h\|^2 dv_g.$$

A map f is called a **harmonic map** if it is a critical point of the energy functional $E(f) = \int_M \|df\|^2 dv_g$. The theory of harmonic maps made a rapid progress during the last fifty years, and gave various applications to other branches in mathematics and physics. From the viewpoint of pullback metrics, the square $\|df\|^2$ of the energy density is the *trace* of the pullback f^*h of the metric. Thus we see the following correspondence between the energy functional $E(f)$ and our functional $F(f)$.

the energy functional in the theory of harmonic maps	our functional
$E(f) = \int_M \ df\ ^2 dv_g$ $= \int_M \text{tr}_g(f^*h) dv_g$	$F(f) = \int_M \ f^*h\ ^2 dv_g.$
the trace of pullback metrics	the norm of pullback metrics

We have some results for the functional $F(f)$. (See Nakauchi-Takenaka [6] and Kawai-Nakauchi [3].) We call a critical point of the functional $F(f)$ a **symphonic map**, compared with a *harmonic map*, since the *norm* contains informations of more components than the *trace* while *symphonies* have more parts than *harmonies*³.

³ This is one of my favorite jokes, and I adopt the term of *symphonic maps*.

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