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ON NATURALITY OF THE HELMHOLTZ OPERATOR

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Abstract. We deduce that all natural operators of the type of the Helmholtz map from the variational calculus in fibered manifolds are the constant multiples of the Helmholtz operator.

0 Introduction

Given two fibered manifolds $Z_1 \to M$ and $Z_2 \to M$ over the same base M, we denote by $\mathcal{C}^\infty_M(Z_1, Z_2)$ the space of all base preserving fibered manifold morphisms of Z_1 into Z_2. In [2], Kolář and Vitolo studied the s-th order Helmholtz map of the variational calculus on a fibered manifold $p : Y \to M$, $\dim M = m$, as a morphism operator

$$H : \mathcal{C}^\infty_Y(J^sY, V^*Y \otimes \bigwedge^m T^*M) \to \mathcal{C}^\infty_{J^sY}(J^{2s}Y, V^*J^sY \otimes V^*Y \otimes \bigwedge^m T^*M)\,.$$

They also deduced that for $s = 1, 2$ all $\mathcal{FM}_{m,n}$-natural operators of this type (in the sense of [1]) are of the form cH, $c \in \mathbf{R}$. In the present paper we deduce that the same result holds for arbitrary s. In other words we prove the following theorem.

Theorem 1. *Let m, n, s be natural numbers with $n \geq 2$. Then any π^{2s}_s-local and $\mathcal{FM}_{m,n}$-natural (regular) operator*

$$D : \mathcal{C}^\infty_Y(J^sY, V^*Y \otimes \bigwedge^m T^*M) \to \mathcal{C}^\infty_{J^sY}(J^{2s}Y, V^*J^sY \otimes V^*Y \otimes \bigwedge^m T^*M)$$

is of the form $D = cH$, $c \in \mathbf{R}$, where $\pi^{2s}_s : J^{2s}Y \to J^sY$ is the jet projection.

From now on $\mathbf{R}^{m,n}$ is the trivial bundle $\mathbf{R}^m \times \mathbf{R}^n \to \mathbf{R}^m$ and $x^1, \dots, x^m$, $y^1, \dots, y^n$ are the usual coordinates on $\mathbf{R}^{m,n}$.

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1 Proof of Theorem 1

Let D be an operator in question.

Since an $\mathcal{FM}_{m,n}$-map $\big(x, y-\sigma(x)\big)$ sends $j^{2s}_0(\sigma)$ into $\Theta = j^{2s}_0(0) \in J^{2s}_0(\mathbf{R}^m, \mathbf{R}^n) = J^{2s}_0(\mathbf{R}^{m,n})$, $J^{2s}(\mathbf{R}^{m,n})$ is the $\mathcal{FM}_{m,n}$-orbit of Θ. Then D is uniquely determined by the evaluations

$$\langle D(E)_\Theta, w \otimes v\rangle \in \bigwedge^m T^*_0\mathbf{R}^m$$

for all $E \in \mathcal{C}^\infty_{\mathbf{R}^{m,n}}\big(J^s(\mathbf{R}^{m,n}), V^*\mathbf{R}^{m,n} \otimes \bigwedge^m T^*\mathbf{R}^m\big)$, $w \in V_{\pi^{2s}_s(\Theta)}J^s(\mathbf{R}^{m,n})$ and $v \in T_0\mathbf{R}^n = V_{(0,0)}\mathbf{R}^{m,n}$.

Using the invariance of D with respect to $\mathcal{FM}_{m,n}$-morphisms of the form $id_{\mathbf{R}^m} \times \psi$ for linear ψ (since $n \geq 2$) we get that D is uniquely determined by the evaluations

$$\Big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(f(x), 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle \in \bigwedge^m T^*_0\mathbf{R}^m$$

for all $E \in \mathcal{C}^\infty_{\mathbf{R}^{m,n}}\big(J^s(\mathbf{R}^{m,n}), V^*\mathbf{R}^{m,n} \otimes \bigwedge^m T^*\mathbf{R}^m\big)$ and all $f : \mathbf{R}^m \to \mathbf{R}$.

Using the invariance of D with respect to $\mathcal{FM}_{m,n}$-maps $(x^1, \dots, x^m, y^1 + f(x)y^1, y^2, \dots, y^n)$ preserving Θ we get that D is uniquely determined by the evaluations

$$\Big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1, 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle \in \bigwedge^m T^*_0\mathbf{R}^m$$

for all $E \in \mathcal{C}^\infty_{\mathbf{R}^{m,n}}\big(J^s(\mathbf{R}^{m,n}), V^*\mathbf{R}^{m,n} \otimes \bigwedge^m T^*\mathbf{R}^m\big)$.

Let $E \in \mathcal{C}^\infty_{\mathbf{R}^{m,n}}\big(J^s(\mathbf{R}^{m,n}), V^*\mathbf{R}^{m,n} \otimes \bigwedge^m T^*\mathbf{R}^m\big)$. Using the invariance of D with respect to $\mathcal{FM}_{m,n}$-maps $\psi_\tau = (x^1, \dots, x^m, \frac{1}{\tau^1}y^1, \dots, \frac{1}{\tau^n}y^n)$ for $\tau^j \neq 0$ we get the homogeneity condition

$$\begin{aligned}&\Big\langle D\big((\psi_\tau)_*E\big)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1, 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\\ &= \tau^1\tau^2\Big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1, 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\end{aligned}$$

for $\tau = (\tau^1, \dots, \tau^n)$. By Corollary 19.8 in [1] of the non-linear Peetre theorem we can assume that E is a polynomial (with arbitrary degree). It is easily seen that coordinates of polynomial $(\psi_\tau)_*E$ are the multiplication by monomials in τ of respective coordinates of polynomial E. The regularity of D implies that $\big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1, 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\big\rangle$ is smooth with respect to the coordinates of E. Then by the homogeneous function theorem (and the above type of homogeneity) we deduce that $\big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1, 0, \dots, 0)\big) \otimes \frac{\partial}{\partial y^2}_0\big\rangle$ depends linearly on the coordinates of E on all $x^\beta y^1_\alpha dy^2 \otimes dx^\mu$ and $x^\beta y^2 dy^1 \otimes dx^\mu$, it depends bilinearly on the coordinates of E on all $x^\rho dy^1 \otimes dx^\mu$ and $x^\beta dy^2 \otimes dx^\mu$, and it is independent of the other coordinates of E, where (x^i, y^j_α) is the induced coordinate system on

$J^s(\mathbf{R}^{m,n})$ and $dx^\mu = dx^1 \wedge \cdots \wedge dx^m$. (Here and from now on α, ρ and β are arbitrary m-tuples with $|\alpha| \le s$).

In other words (and more precisely) $\left\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\right\rangle$ is determined by the values

$$\Big\langle D(x^\beta y^2_\alpha dy^1 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle,$$
$$\Big\langle D(x^\beta y^1_\alpha dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle,$$
$$\Big\langle D(x^\rho dy^1 \otimes dx^\mu + x^\beta dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle.$$

Moreover

$$\Big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle$$

is linear in E for E from the vector subspace (over $\mathbf{R}$) spaned by all $x^\beta y^1_\alpha dy^2 \otimes dx^\mu$ and $x^\beta y^2_\alpha dy^1 \otimes dx^\mu$,

$$\begin{aligned}&\Big\langle D(dy^1 \otimes dx^\mu + E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\\ &=\Big\langle D(E)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\end{aligned} \tag{1}$$

for E from the vector subspace (over $\mathbf{R}$) spaned by all $x^\beta y^1_\alpha dy^2 \otimes dx^\mu$ and $x^\beta y^2_\alpha dy^1 \otimes dx^\mu$, and

$$\begin{aligned}&\Big\langle D(ax^\rho dy^1 \otimes dx^\mu + bx^\beta dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\\ &=ab\Big\langle D(x^\rho dy^1 \otimes dx^\mu + x^\beta dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\end{aligned} \tag{2}$$

for all real numbers a and b.

Then by the invariance of D with respect to $(\tau^1 x^1, \dots, \tau^m x^m, y^1, \dots, y^n)$ for $\tau^i \neq 0$ we get

$$\begin{aligned}&\Big\langle D(x^\beta y^2_\alpha dy^1 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle\\ &=\Big\langle D(x^\beta y^1_\alpha dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle = 0\end{aligned} \tag{3}$$

if only $\beta \neq \alpha$, and

$$\Big\langle D(x^\rho dy^1 \otimes dx^\mu + x^\beta dy^2 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0\big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0\Big\rangle = 0$$

for all ρ and β.

Suppose $\alpha=(\alpha_1,\dots,\alpha_m)$ be an m-tuple with $|\alpha|\le s$ and $\alpha_i\neq 0$ for some i. Then using the invariance of D with respect to locally defined $\mathcal{FM}_{m,n}$-map $\psi=(x^1,\dots,x^m,y^1,y^2+x^iy^2\dots,y^n)^{-1}$ preserving $x^1,\dots,x^m$, y^1, Θ, $j^s_0(1,0,\dots,0)$ and $\frac{\partial}{\partial y^2}{}_0$ and sending y^2_α into $y^2_\alpha+x^iy^2_\alpha+y^2_{\alpha-1_i}$ $\big($as $y^2_\alpha\circ J^s\psi^{-1}(j^s_{x_0}\sigma)=\partial_\alpha(\sigma^2+x^i\sigma^2)(x_0)=\partial_\alpha\sigma^2(x_0)+x^i_0\partial_\alpha\sigma^2(x_0)+\partial_{\alpha-1_i}\sigma^2(x_0)=(y^2_\alpha+x^iy^2_\alpha+y^2_{\alpha-1_i})(j^s_{x_0}\sigma)$ for $j^s_{x_0}\sigma\in J^s\mathbf{R}^{m,n}$, where $\partial\alpha$ is the iterated partial derivative with erspect to the index α multiplied by $\frac{1}{\alpha!}\big)$ from

$$\Big\langle D(x^{\alpha-1_i}y^2_\alpha dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle=0$$

(see (3)) we deduce that

$$\begin{aligned}&\Big\langle D(x^{\alpha}y^2_\alpha dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle\\&=-\Big\langle D(x^{\alpha-1_i}y^2_{\alpha-1_i}dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle.\end{aligned}$$

Then for any m-tuple α with $|\alpha|\le s$ we have

$$\begin{aligned}&\Big\langle D(x^{\alpha}y^2_\alpha dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle\\&=(-1)^{|\alpha|}\Big\langle D(y^2_{(0)}dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle.\end{aligned}$$

By the same arguments (since ψ sends dy_2 into $dy^2+x^idy^2$) from

$$\Big\langle D(x^{\alpha-1_i}y^1_\alpha dy^2\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle=0$$

we obtain

$$\Big\langle D(x^{\alpha}y^1_\alpha dy^2\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle=0$$

if $\alpha\neq(0)$.

Using the invariance of D with respect to (locally defined) $\mathcal{FM}_{m,n}$-map $(x^1,\dots,x^m,y^1+y^1y^2,\dots,y^n)^{-1}$ preserving Θ, $j^s_0(1,0,\dots,0)$ and $\frac{\partial}{\partial y^2}{}_0$ from

$$\Big\langle D(dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle=0$$

(see (2)) and (1) we deduce that

$$\begin{aligned}&\Big\langle D(y^2_{(0)}dy^1\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle\\&=-\Big\langle D(y^1_{(0)}dy^2\otimes dx^\mu)_\Theta,\frac{d}{dt}{}_0\big(tj^s_0(1,0,\dots,0)\big)\otimes\frac{\partial}{\partial y^2}{}_0\Big\rangle.\end{aligned}$$

Then D is uniquely determined by

$$\Big\langle D(y^2_{(0)}dy^1 \otimes dx^\mu)_\Theta, \frac{d}{dt}_0 \big(tj^s_0(1,0,\dots,0)\big) \otimes \frac{\partial}{\partial y^2}_0 \Big\rangle \in \bigwedge^m T^*_0\mathbf{R}^m = \mathbf{R}\,.$$

Then the vector space of all D in question is of dimension less or equal to 1. That is why $D = cH$ for some $c \in \mathbf{R}$. □

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