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This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/68609> since 2017-11-27T09:39:29Z

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(Article begins on next page)

Bergman–Bianchi identities in field theories*

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Abstract

We relate the generalized Bergman–Bianchi identities for Lagrangian field theories on gauge-natural bundles with the kernel of the associated gauge-natural Jacobi morphism.

2000 MSC: 58A20,58A32,58E30,58E40,58J10,58J70.

Key words: gauge-natural bundles, Bergman–Bianchi identities, Jacobi morphisms.

1 The Bergman–Bianchi morphism

Our general framework is the calculus of variations on finite order *gauge-natural bundles* [3, 8]. Such geometric structures have been widely recognized to suitably describe so-called gauge-natural field theories, *i.e.* physical theories in which right-invariant infinitesimal automorphisms of the structure bundle \mathbf{P} uniquely define the transformation laws of the fields themselves (see *e.g.* [4] and references quoted therein). We shall in particular consider *finite order variational sequences on gauge-natural bundles*, whereby fundamental objects of calculus of variations such as Lagrangians, Euler–Lagrange and Jacobi morphisms are conveniently represented as quotient morphisms (see *e.g.* [9, 6]). For basic notions and fixing notation we refer to [1, 3, 4, 5, 6, 8, 11] and references therein.

*Work partially supported by MIUR (PRIN 2003) and University of Torino

Recall that generalized Bergman–Bianchi identities for field theories are necessary and (locally) sufficient conditions for the Noether conserved current to be not only closed but also the divergence of a skew-symmetric (tensor) density along solutions of the Euler–Lagrange equations [1]. It was also stressed that in the general theory of relativity these identities coincide with the contracted Bianchi identities for the curvature tensor of the pseudo-Riemannian metric.

Let \mathbf{Y}_ζ be a gauge-natural bundle and let λ be a gauge-natural Lagrangian [4, 8] on the s -th order prolongation $J_s\mathbf{Y}_\zeta$. Let $\mathcal{A}^{(r,k)}$ be the vector bundle of right-invariant principal automorphisms of the underlying principal structure bundle \mathbf{P} . In the following we shall consider variation vector fields which are vertical parts of gauge-natural lifts of a given $\bar{\Xi} \in \mathcal{A}^{(r,k)}$. Let $\mathcal{C}_{2s}^*[\mathcal{A}^{(r,k)}] \simeq J_{2s+1}\mathcal{A}^{(r,k)} \times_{J_{2s}\mathcal{A}^{(r,k)}} V J_{2s}\mathcal{A}^{(r,k)}$. By a slight abuse of notation, we denote by $\mathfrak{G}(\bar{\Xi})_V$ the vertical part – with respect to the contact structure induced by the projections $J_{s+1}\mathbf{Y}_\zeta \rightarrow J_s\mathbf{Y}_\zeta$ – of (jet prolongation of) the gauge-natural lift $\mathfrak{G}(\bar{\Xi})$ [3, 4, 5]. We set

$$\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V) \equiv \mathcal{L}_{\bar{\Xi}} \mathcal{E}_n(\lambda) : J_{2s}\mathbf{Y}_\zeta \rightarrow \mathcal{C}_{2s}^*[\mathcal{A}^{(r,k)}] \otimes \mathcal{C}_0^*[\mathcal{A}^{(r,k)}] \wedge (\wedge^n T^*\mathbf{X}), \quad (1)$$

where $\mathcal{L}_{\bar{\Xi}}$ is the Lie derivative operator acting on sections of the gauge-natural bundle [5], \lrcorner is the interior product and $\mathcal{E}_n(\lambda)$ is the generalized Euler-Lagrange morphism associated with λ [6]. The morphism $\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)$ so defined is a generalized Lagrangian associated with the field equations of the original Lagrangian λ and it has been considered in applications *e.g.* in General Relativity. By the linearity of \mathcal{L} we can regard $\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)$ as the extended morphism defined on $J_{2s}\mathbf{Y}_\zeta \times_{\mathbf{X}} V J_{2s}\mathcal{A}^{(r,k)}$. We have $D_H\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V) = 0$, where D_H is the exterior differential; thus, as a consequence of a global decomposition formula for vertical morphisms [7], we can state the following [11].

Lemma 1 *Let $\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)$ be as above. On the domain of $\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)$ we have (up to pull-backs):*

$$\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V) = \beta(\lambda, \mathfrak{G}(\bar{\Xi})_V) + F_{\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)},$$

where

$$\beta(\lambda, \mathfrak{G}(\bar{\Xi})_V) \equiv E_{\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)}$$

and, locally, $F_{\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)} = D_H M_{\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)}$.

Definition 1 We call the global morphism $\beta(\lambda, \mathfrak{G}(\bar{\Xi})_V) := E_{\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)}$ the *generalized Bergman–Bianchi morphism* associated with the Lagrangian λ and the variation vector field $\bar{\Xi}$. \square

Let \mathfrak{K} be the *kernel* of $\mathcal{J}(\lambda, \mathfrak{G}(\bar{\Xi})_V)$. We have the following characterization of the Bergman–Bianchi identities for gauge-natural theories [11].

Theorem 1 *The generalized Bergman–Bianchi morphism is globally vanishing for the variation vector field $\bar{\Xi}$ if and only if $\delta_{\mathfrak{G}}^2 \lambda \equiv \mathcal{J}(\lambda, \mathfrak{G}(\bar{\Xi})_V) = 0$, i.e. if and only if $\mathfrak{G}(\bar{\Xi})_V \in \mathfrak{K}$.*

From now on we shall write $\omega(\lambda, \mathfrak{K})$ to denote $\omega(\lambda, \mathfrak{G}(\bar{\Xi})_V)$ when $\mathfrak{G}(\bar{\Xi})_V$ belongs to \mathfrak{K} . Analogously for β and other morphisms.

First of all let us make the following important consideration. Let $\mathcal{L}_{j_s \bar{\Xi}}$ be the variational Lie derivative operator [6] acting on generalized variational morphisms.

Proposition 1 *For each $\bar{\Xi} \in \mathcal{A}^{(r,k)}$ such that $\bar{\Xi}_V \in \mathfrak{K}$, we have*

$$\mathcal{L}_{j_s \bar{\Xi}_H} \omega(\lambda, \mathfrak{K}) = -D_H(-j_s \mathcal{L}_{\bar{\Xi}}] p_{D_V \omega(\lambda, \mathfrak{K})}). \quad (2)$$

PROOF. We have

$$\mathcal{L}_{j_s \bar{\Xi}_V} \omega(\lambda, \mathfrak{K}) = \mathcal{L}_{j_s \bar{\Xi}_V} \mathcal{L}_{j_s \bar{\Xi}} \lambda = \mathcal{L}_{j_s [\bar{\Xi}_V, \bar{\Xi}_H]} \lambda.$$

On the other hand it is also easy to verify that

$$\mathcal{L}_{j_s \bar{\Xi}_H} \omega(\lambda, \mathfrak{K}) = \mathcal{L}_{j_s [\bar{\Xi}_H, \bar{\Xi}_V]} \lambda = -\mathcal{L}_{j_s \bar{\Xi}_V} \omega(\lambda, \mathfrak{K}).$$

Since

$$\begin{aligned} \mathcal{L}_{j_s \bar{\Xi}_V} \omega(\lambda, \mathfrak{K}) &= -\mathcal{L}_{\bar{\Xi}}] \mathcal{E}_n(\omega(\lambda, \mathfrak{K})) + D_H(-j_s \mathcal{L}_{\bar{\Xi}}] p_{D_V \omega(\lambda, \mathfrak{K})}) = \\ &= \beta(\lambda, \mathfrak{K}) + D_H(-j_s \mathcal{L}_{\bar{\Xi}}] p_{D_V \omega(\lambda, \mathfrak{K})}), \end{aligned}$$

from the Theorem above we get the assertion. \square

The new generalized Lagrangian $\omega(\lambda, \mathfrak{K})$ is gauge-natural invariant too, i.e. $\mathcal{L}_{j_s \bar{\Xi}} \omega(\lambda, \mathfrak{K}) = 0$.

Even more, we can state the following

Proposition 2 *Let $\bar{\Xi}_V \in \mathfrak{K}$. We have*

$$\mathcal{L}_{j_s \bar{\Xi}_H} \omega(\lambda, \mathfrak{K}) = 0. \quad (3)$$

Corollary 1 Let $\bar{\Xi}_V \in \mathfrak{K}$. We have the covariant conservation law

$$D_H(-j_s \mathcal{L}_{\bar{\Xi}}] p_{D_V \omega(\lambda, \mathfrak{K})}) = 0. \quad (4)$$

Definition 2 We define the covariantly conserved current

$$\mathcal{H}(\lambda, \mathfrak{K}) = -j_s \mathcal{L}_{\bar{\Xi}}] p_{D_V \omega(\lambda, \mathfrak{K})}, \quad (5)$$

to be a Hamiltonian form for $\omega(\lambda, \mathfrak{K})$ (in the sense of [10]). \square

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