Formal Poisson cohomology of r-matrix induced quadratic structures*

Mohsen Masmoudi[†], Norbert Poncin[‡]

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1 Introduction

The Poisson-Lichnerowicz complex is originated from Deformation Quantization, but receives increasing attention inter alia by algebraists. It is related with Kontsevich's formality theorem and the corresponding Hochschild cohomology, and appears naturally as well in explicit step-by-step constructions of star-products, as in deformation theory of Poisson tensors. Moreover, Poisson cohomology is closely linked with singularities of the underlying Poisson structure and contains encoded information about the topology of the leaf space and the change of the symplectic structure.

2 r-matrix induced Poisson tensors

Poisson structures generated by an r-matrix are of importance e.g. in Deformation Quantization, in particular in view of Drinfeld's method.

Set $G = \mathrm{GL}(n, \mathbb{R})$ and $\mathfrak{g} = \mathrm{gl}(n, \mathbb{R})$. The well-known Lie algebra isomorphism between $\mathfrak{g}$ and the algebra $\mathcal{X}_0^1(\mathbb{R}^n)$ of linear vector fields, extends to a Gerstenhaber algebra homomorphism $J : \wedge\mathfrak{g} \to \bigoplus_k \left(\mathcal{S}^k(\mathbb{R}^n)^* \otimes \wedge^k\mathbb{R}^n\right)$. Its restriction

$$J^k : \wedge^k\mathfrak{g} \to \mathcal{S}^k(\mathbb{R}^n)^* \otimes \wedge^k\mathbb{R}^n$$

is onto, but has a non-trivial kernel if $k, n \geq 2$. In particular,

$$J^3[r, r] = [J^2r, J^2r],\ r \in \mathfrak{g} \wedge \mathfrak{g},$$

where $[., .]$ is the Schouten bracket. These observations allow to understand that the characterization of the quadratic Poisson structures that are implemented by an r-matrix, is an open problem.

Quadratic Poisson tensors Λ_1 and Λ_2 are equivalent if and only if there is $A \in G$ such that $A_*\Lambda_1 = \Lambda_2$, where $*$ denotes the standard action of G on tensors of $\mathbb{R}^n$. As J^2 is a G-module homomorphism, i.e.

$$A_*(J^2r) = J^2(\mathrm{Ad}(A)r),$$

the orbit of an r-matrix induced quadratic structure is made up by such structures. Let $\Lambda = J^2r$ be a quadratic Poisson tensor implemented by a bimatrix $r \in \mathfrak{g} \wedge \mathfrak{g}$. In order to determine wether this tensor is generated by an r-matrix, we have to take an interest in the preimage under J^2 of the orbit O_Λ of Λ. This preimage is the disjoint union

$$(J^2)^{-1}(O_\Lambda) = \cup_{r\in(J^2)^{-1}\Lambda} O_r$$

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†Institut Elie Cartan, Université Henri Poincaré, B.P. 239, F-54 506 Vandoeuvre-les-Nancy Cedex, France, E-mail: Mohsen.Masmoudi@iecn.u-nancy.fr

‡University of Luxembourg, Campus Limpertsberg, Mathematics Laboratory, 162A, avenue de la Faïencerie, L-1511 Luxembourg City, Grand-Duchy of Luxembourg, E-mail: norbert.poncin@uni.lu

of the orbits O_r of all the bimatrices r that are mapped on Λ by J^2. The chances that this fiber bundle intersects with r-matrices are the bigger, the smaller is O_Λ. In other words, the dimension of the isotropy Lie group G_Λ of Λ, or of its Lie algebra, the stabilizer

$$\mathfrak{g}_\Lambda = \{a \in \mathfrak{g} : [\Lambda, Ja] = 0\}$$

of Λ for the corresponding infinitesimal action, should be big enough.

In $\mathbb{R}^3$, a quadratic Poisson tensor Λ is induced by an r-matrix, if $\dim \mathfrak{g}_\Lambda \geq 3$. For tensor $\Lambda = (x_1^2 + x_2x_3)\partial_2 \wedge \partial_3$, $\partial_i = \partial/\partial_{x_i}$, for instance, which is not r-matrix induced, this dimension is $\dim \mathfrak{g}_\Lambda = 2$. If stabilizer $\mathfrak{g}_\Lambda$ has a sufficiently high dimension, structure Λ is defacto implemented by an r-matrix $r \in \mathfrak{g}_\Lambda \wedge \mathfrak{g}_\Lambda$ that belongs to this stabilizer. More precisely, there exist matrices $A_1, A_2, A_3 \in \mathfrak{g}$, such that $[A_i, A_j] = 0$ and $\Lambda = J^2 \left(c_1 A_2 \wedge A_3 + c_2 A_3 \wedge A_1 + c_3 A_1 \wedge A_2\right)$, $c_1, c_2, c_3 \in \mathbb{R}$. Our cohomological technique applies to the preceding family of structures, i.e. to those tensors that read as linear combination

$$\Lambda = c_1 Y_2 \wedge Y_3 + c_2 Y_3 \wedge Y_1 + c_3 Y_1 \wedge Y_2$$

of wedge products of three mutually commuting linear vector fields $Y_i = JA_i$. The classes of the Dufour-Haraki classification (DHC) could be classified according to their membership in our family, which actually contains most of these classes.

3 Cohomological technique

3.1 Simplified differential

The advantage of the just defined family of admissible tensors is readily understood. If we substitute the Y_i for the standard basic vector fields ∂_i, the cochains assume, broadly speaking, the shape

$$\sum f\mathbf{Y},$$

where f is a function and $\mathbf{Y}$ is a wedge product of basic fields Y_i. Then—due to the commutativity of the Y_i—the Lichnerowicz-Poisson coboundary operator $\partial_\Lambda = [\Lambda, \cdot]$ is just

$$\partial_\Lambda(f\mathbf{Y}) = [\Lambda, f\mathbf{Y}] = [\Lambda, f] \wedge \mathbf{Y}.$$

This simplification of the coboundary operator is of course not restricted to the three-dimensional context.

3.2 Short exact sequence of differential spaces

If a cochain is decomposed in the new Y_i-induced basis, its coefficients are rational with fixed denominator, i.e. each cochain C reads

$$C = \sum \frac{p}{D}\mathbf{Y},$$

where $p \in \mathcal{S}(\mathbb{R}^3)^*$ and where $D \in \mathcal{S}^3(\mathbb{R}^3)^*$ is fixed. Conversely, a sum of this type is implemented by a cochain if and only if specific divisibility conditions are met. Hence a natural injection of the *real cochain space* $\mathcal{R}$ into a larger *potential cochain space* $\mathcal{P}$. Let $\mathcal{S}$ be a *supplementary cochain space* of $\mathcal{R}$ in $\mathcal{P}$:

$$\mathcal{P} = \mathcal{R} \oplus \mathcal{S}.$$

Spaces $\mathcal{R}$ and $\mathcal{P}$ are differential spaces for the Lichnerowicz-Poisson coboundary operator ∂_Λ. We can heave space $\mathcal{S}$ also into the category of differential spaces. It suffices to set

$$\partial_\mathcal{S} s := p_\mathcal{S} \partial_\Lambda s,$$

where $s \in \mathcal{S}$ and where $p_\mathcal{S}$ denotes the projection of $\mathcal{P}$ onto $\mathcal{S}$. Projection

$$\phi s := p_\mathcal{R} \partial_\Lambda s$$

of $\partial_\Lambda s$ onto $\mathcal{R}$ defines an anti-homomorphism $\phi : \mathcal{S} \to \mathcal{R}$ of differential spaces. We end up with a short exact sequence of differential spaces

$$0 \to (\mathcal{R}, \partial_\Lambda) \overset{i}{\to} (\mathcal{P}, \partial_\Lambda) \overset{p_{\mathcal{S}}}{\to} (\mathcal{S}, \partial_{\mathcal{S}}) \to 0,$$

where i is the injection of $\mathcal{R}$ into $\mathcal{P}$. This sequence induces in cohomology an exact triangle

$$\begin{tikzcd} H(\mathcal{R}) \arrow[rr, "i_\sharp"] & & H(\mathcal{P}) \arrow[dl, "(p_{\mathcal{S}})_\sharp"] \\ & H(\mathcal{S}) \arrow[ul, "\phi_\sharp"] & \end{tikzcd}$$

When computing the Poisson-Lichnerowicz cohomology of the examined admissible quadratic Poisson structure—i.e. the $\mathcal{R}$-cohomology—in the Y_i-basis, we naturally encounter coboundaries of potential cochains. The preceding exact triangle has been contrived in order to avoid checking systematically if these coboundaries represent non-trivial cohomology classes. It actually turns out that $\mathcal{P}$-cohomology and $\mathcal{S}$-cohomology are less intricate than $\mathcal{R}$-cohomology and are important stages on the way to $\mathcal{R}$-cohomology. For instance, if $\phi_\sharp$ vanishes, we have $H(\mathcal{R}) = H(\mathcal{P})/H(\mathcal{S})$.

4 Cohomology of structure 2 of the DHC

The second class of the Dufour-Haraki classification (DHC) may be represented by tensor

$$\begin{aligned} \Lambda &= b(x_1^2 + x_2^2)\partial_1 \wedge \partial_2 + (2bx_1 - ax_2)x_3\partial_2 \wedge \partial_3 + (ax_1 + 2bx_2)x_3\partial_3 \wedge \partial_1 \\ &= 2bY_2 \wedge Y_3 + aY_3 \wedge Y_1 + bY_1 \wedge Y_2, \end{aligned}$$

where $a \in \mathbb{R}, b \in \mathbb{R}^*$, and where

$$Y_1 = x_1\partial_1 + x_2\partial_2, Y_2 = x_1\partial_2 - x_2\partial_1, Y_3 = x_3\partial_3$$

are mutually commuting linear vector fields.

We denote the determinant $(x_1^2 + x_2^2)x_3$ of the vector fields Y_i by D. The results of this article will entail that the abundance of cocycles that do not bound is tightly related with closeness of the considered Poisson tensor to Koszul-exactness. If $a = 0$, structure Λ is exact and induced by bD. The algebra of Casimir functions is generated by 1 if $a \neq 0$ and by D if $a = 0$. When rewording this statement, we get

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \begin{cases} \mathbb{R}, & \text{if} \quad a \neq 0, \\ \bigoplus_{m=0}^{\infty} \mathbb{R}D^m, & \text{if} \quad a = 0. \end{cases}$$

Remind now that our Poisson tensor is built with linear infinitesimal Poisson automorphisms Y_i. It follows that the wedge products of the Y_i constitute "a priori" privileged cocycles. Of course, 2-cocycle Λ itself, is a linear combination of such privileged cocycles. Moreover, the curl or modular vector field reads here $K(\Lambda) = a(2Y_3 - Y_1)$ and is thus also a combination of privileged cocycles. As the Lichnerowicz-Poisson cohomology is an associative graded commutative algebra, the first cohomology group of Λ is easy to conjecture:

$$H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda)Y_i.$$

It is well-known that the singularities of the Poisson structure appear in the second and third cohomology spaces. Observe that the singular points of the investigated structure Λ are the annihilators of $D' = x_1^2 + x_2^2$. Note also that any homogeneous polynomial $P \in \mathbb{R}[x_1, x_2, x_3]$ of order m reads

$$P = \sum_{\ell=0}^{m} x_3^\ell P_\ell(x_1, x_2) = \sum_{\ell=0}^{m} x_3^\ell \left(D' \cdot Q_\ell + A_\ell x_1^{m-\ell} + B_\ell x_1^{m-\ell-1}x_2\right),$$

with self-explaining notations. Let us define the polynomial ring of the set of singularities as the quotient of $\mathbb{R}[x_1, x_2, x_3]$ by the ideal generated by D', i.e. as the direct sum

$$\bigoplus_{m=0}^{\infty} \bigoplus_{\ell=0}^{m} x_3^{\ell} \left(\mathbb{R} x_1^{m-\ell} + \mathbb{R} x_1^{m-\ell-1} x_2 \right).$$

The third cohomology group contains a part of this formal series. More precisely,

$$H^3(\Lambda) = \mathrm{Cas}(\Lambda)\ Y_{123} \oplus \begin{cases} \mathbb{R}\ \partial_{123}, & \text{if} \quad a \neq 0, \\ \bigoplus_{m=0}^{\infty} \mathbb{R}\ x_3^m \partial_{123} \oplus \bigoplus_{m=0}^{\infty} x_1^m \left(\mathbb{R} x_1 + \mathbb{R} x_2 \right) \partial_{123}, & \text{if} \quad a = 0, \end{cases}$$

where Y_{123} (resp. ∂_{123}) means $Y_1 \wedge Y_2 \wedge Y_3$ (resp. $\partial_1 \wedge \partial_2 \wedge \partial_3$). The reader might object that the "mother-structure" Λ is symmetric in x_1, x_2 and that there should therefore exist a symmetric "twin-cocycle" $\bigoplus_{m=0}^{\infty} x_2^m (\mathbb{R} x_1 + \mathbb{R} x_2) \partial_{123}$. This cocycle actually exists, but is—as easily checked—cohomologous to the visible representative. Finally, the second cohomology space reads

$$\begin{aligned} H^2(\Lambda) = \;& \mathrm{Cas}(\Lambda) Y_{23} \oplus \mathrm{Cas}(\Lambda) Y_{31} \oplus \mathrm{Cas}(\Lambda) Y_{12} \\ & \oplus \begin{cases} /\,, & \text{if} \quad a \neq 0, \\ \bigoplus_{m=0}^{\infty} \mathbb{R}\ x_3^m \partial_{12} \oplus \bigoplus_{m=0}^{\infty} x_1^{m-1} \left(\mathbb{R} x_1 \partial_{23} + \mathbb{R}(x_1 \partial_{31} + m x_2 \partial_{23}) \right), & \text{if} \quad a = 0. \end{cases} \end{aligned}$$

For $m \geq 1$, the last cocycle has the form

$$\left(\mathbb{R} x_1^m + \mathbb{R} x_1^{m-1} x_2 \right) \partial_{23} + \left(\int \partial_{x_2} \left(\mathbb{R} x_1^m + \mathbb{R} x_1^{m-1} x_2 \right) dx_1 \right) \partial_{31}$$

and is thus also induced by singularities.

5 Cohomology of structure 7 of the DHC

In this section, we provide complete results regarding the formal cohomology of structure 7 of the DHC,

$$\Lambda_7 = b(x_1^2 + x_2^2) \partial_1 \wedge \partial_2 + ((2b + c) x_1 - a x_2) x_3 \partial_2 \wedge \partial_3 + (a x_1 + (2b + c) x_2) x_3 \partial_3 \wedge \partial_1.$$

We assume that $c \neq 0$, otherwise we recover structure 2.

In the following theorems, the Y_i $(i \in \{1, 2, 3\})$ denote the same vector fields as above, namely,

$$Y_1 = x_1 \partial_1 + x_2 \partial_2, Y_2 = x_1 \partial_2 - x_2 \partial_1, Y_3 = x_3 \partial_3.$$

Moreover, we set

$$D' = x_1^2 + x_2^2, D = (x_1^2 + x_2^2) x_3.$$

If $\frac{b}{c} \in \mathbb{Q}, b(2b + c) < 0$, we denote by $(\beta, \gamma) \simeq (b, c)$ the irreducible representative of the rational number $\frac{b}{c}$, with positive denominator, $\beta \in \mathbb{Z}, \gamma \in \mathbb{N}^*$. If $\frac{b}{c} \in \mathbb{Q}, b(2b+c) > 0$, $(\beta, \gamma) \simeq (b, c)$ denotes the irreducible representative with positive numerator, $\beta \in \mathbb{N}^*, \gamma \in \mathbb{Z}^*$. Furthermore, we write Λ instead of Λ_7, $\bigoplus_{ij} \mathrm{Cas}(\Lambda) Y_{ij}$ instead of $\mathrm{Cas}(\Lambda) Y_{23} + \mathrm{Cas}(\Lambda) Y_{31} + \mathrm{Cas}(\Lambda) Y_{12}$, $\mathrm{Sing}(\Lambda) = \bigoplus_{r \geq 0} \mathrm{Sing}^r(\Lambda)$ instead of $\mathbb{R}[[x_3]] = \bigoplus_{r \geq 0} \mathbb{R} x_3^r$, and $C_\gamma Y_3$ $(\gamma \in \{2, 4, 6, \ldots\})$ instead of $\mathbb{R} D'^{\frac{\gamma}{2} - 1} x_3^{-1} Y_3 = \mathbb{R} D'^{\frac{\gamma}{2} - 1} \partial_3$.

Theorem 1. *If $a \neq 0$, the cohomology spaces are*

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \mathbb{R}, \quad H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda) Y_i,$$

$$H^2(\Lambda) = \bigoplus_{ij} \mathrm{Cas}(\Lambda) Y_{ij}, \quad H^3(\Lambda) = \mathrm{Cas}(\Lambda) Y_{123} \oplus \mathrm{Sing}^0(\Lambda) \partial_{123}$$

Theorem 2. *If $a = 0$ and $b = 0$, the cohomology is*

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \bigoplus_{r\geq 0} \mathbb{R}D'^r, \quad H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda)Y_i,$$

$$H^2(\Lambda) = \bigoplus_{ij} \mathrm{Cas}(\Lambda)Y_{ij} \oplus \mathrm{Sing}(\Lambda)\partial_{12}, \quad H^3(\Lambda) = \mathrm{Cas}(\Lambda)Y_{123} \oplus \mathrm{Sing}(\Lambda)\partial_{123}$$

Theorem 3. *If $a = 0$ and $2b + c = 0$, the cohomology groups are*

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \bigoplus_{r\geq 0} \mathbb{R}x_3^r, \quad H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda)Y_i \oplus C_2Y_3,$$

$$H^2(\Lambda) = \bigoplus_{ij} \mathrm{Cas}(\Lambda)Y_{ij} \oplus \mathrm{Sing}(\Lambda)\partial_{12} \oplus C_2Y_3 \wedge (\mathbb{R}Y_1 + \mathbb{R}Y_2),$$

$$H^3(\Lambda) = \mathrm{Cas}(\Lambda)Y_{123} \oplus \mathrm{Sing}(\Lambda)\partial_{123} \oplus C_2Y_3 \wedge \mathbb{R}Y_{12}$$

Theorem 4. *If $a = 0$ and $\frac{b}{c} \notin \mathbb{Q}$ or $\frac{b}{c} \in \mathbb{Q}, b(2b + c) < 0$,*

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \mathbb{R}, \quad H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda)Y_i \oplus \begin{cases} (b,c) \simeq (-1,\gamma), \gamma \in \{4,6,8,\ldots\} : C_\gamma Y_3 \\ otherwise : 0 \end{cases},$$

$$H^2(\Lambda) = \bigoplus_{ij} \mathrm{Cas}(\Lambda)Y_{ij} \oplus \mathrm{Sing}(\Lambda)\partial_{12} \oplus \begin{cases} (b,c) \simeq (-1,\gamma), \gamma \in \{4,6,8,\ldots\} : \\ C_\gamma Y_3 \wedge (\mathbb{R}Y_1 + \mathbb{R}Y_2) \\ otherwise : \\ 0 \end{cases},$$

$$H^3(\Lambda) = \mathrm{Cas}(\Lambda)Y_{123} \oplus \mathrm{Sing}(\Lambda)\partial_{123} \oplus \begin{cases} (b,c) \simeq (-1,\gamma), \gamma \in \{4,6,8,\ldots\} : C_\gamma Y_3 \wedge \mathbb{R}Y_{12} \\ otherwise : 0 \end{cases}$$

Theorem 5. *If $a = 0$ and $\frac{b}{c} \in \mathbb{Q}, b(2b + c) > 0$,*

$$H^0(\Lambda) = \mathrm{Cas}(\Lambda) = \bigoplus_{n\in\mathbb{N}, n\gamma\in 2\mathbb{Z}} \mathbb{R}D'^{n\beta+\frac{n\gamma}{2}}x_3^{n\beta}, \quad H^1(\Lambda) = \bigoplus_i \mathrm{Cas}(\Lambda)Y_i,$$

$$H^2(\Lambda) = \bigoplus_{ij} \mathrm{Cas}(\Lambda)Y_{ij} \oplus \mathrm{Sing}(\Lambda)\partial_{12}, \quad H^3(\Lambda) = \mathrm{Cas}(\Lambda)Y_{123} \oplus \mathrm{Sing}(\Lambda)\partial_{123}$$

6 Comments and outlook

The preceding results allow to ascertain that Casimir functions are closely related with Koszul-exactness or "quasi-exactness" of the considered structure. Observe that $C_\gamma = \mathbb{R}D'^{-1+\frac{\gamma}{2}}x_3^{-1}$ ($\gamma \in \{2,4,6,\ldots\}$) has the same form as the basic Casimir in Theorem 5 and that the negative superscript in x_3^{-1} can only be compensated via multiplication by $Y_3 = x_3\partial_3$. Clearly, such a compensation is not possible for $\mathbb{R}D'^{-n+\frac{n\gamma}{2}}x_3^{-n}$, $n > 1$. Hence cocycle $C_\gamma Y_3$ is in some sense "Casimir-like" and "accidental". Note eventually that the "weight" of the singularities in cohomology increases with closeness of the considered Poisson structure to Koszul-exactness.

The cohomology of the other r-matrix induced Poisson tensors of the DHC is being computed by means of similar methods. Moreover, we are computing the cohomology of non-admissible quadratic structures, using spectral sequences.

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