Bicovariant Differential Geometry of the Quantum Group $SL_h(2)$

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Abstract

There are only two quantum group structures on the space of two by two unimodular matrices, these are the $SL_q(2)$ and the $SL_h(2)$ [9-13] quantum groups. One can not construct a differential geometry on $SL_q(2)$, which at the same time is bicovariant, has three generators, and satisfies the Liebnitz rule. We show that such a differential geometry exists for the quantum group $SL_h(2)$ and derive all of it’s properties.
1 Introduction

One can look at a quantum group in two different ways: As the quantization of the algebra of functions on a poisson-Lie group [1,2], or as a quantum automorphism group acting on a non-commuting space [3].

The former point of view is best suited for revealing the mathematical unity of integrable models [1,4]. If one demands that, the process of quantization, preserves some natural properties of the poisson Lie groups, then it can be shown that the resulting quantum group will be unique. This is the quantization in the sense of Drinfeld [1].

The second point of view is however best suited for the application of quantum group in formulating physical theories like quantum mechanics and field theory, on non-commuting space time [5,7]. This second approach is however not as rigid as the first one, and one can imagine quantum spaces with a variety of defining relations, which will lead to different quantum groups. It’s therefore natural to seek for criteria that restricts the set of quantum spaces and hence quantum groups. One such criteria is the demand of the existence of a central determinant in the quantum matrix group.

Fortunately, in the space of two by two matrices this demand, restricts the quantum groups to only two classes [8,9]. These are the $SL_q(2)$ and the $SL_h(2)$ quantum groups.

The latter was first introduced in [10] for the case of $h = 1$, where it was called the Jordanian deformation of $sl(2)$. The continuous parameter $h$ was then introduced in [11]. Later the quantized universal enveloping algebra $U_h(sl(2))$ was found [12], and finally, the quantum planes [13,14] and the structure of the quantum De Rham Complexes on the plane $R_h(2)$ and the group $SL_h(2)$ were constructed [13].

In the light of the non-commutative Geometry [15] and it’s possible relevance to physics [16], the explicit construction of all the objects characterizing the differential geometry of a quantum group is important. This is true especially for the simplest quantum group $SL_q(2)$ and $SL_h(2)$. Following the pioneering work of Woronowics [17], Bicovariant differential Geometries have been constructed for many compact and non compact q-groups [18,19]. In this paper we construct the Bi-covariant differential geometry of $SL_h(2)$.

The structure of this paper is as follows: In section 2, we describe the $SL_h(2)$ quantum group and the quantum De Rham Complex on it. In section 3, we describe our basic strategy for completing the structure of the bicovariant differential geometry of $SL_h(2)$. Section 4 gives the explicit results and formulas for various differential geometric objects.
pertaining to $SL_h(2)$. Finally, in section 5, we use the algebra of vector fields on $SL_h(2)$ we derive a new deformations of the $sl(2)$ algebra, admitting a truly quadratic casimiar.

2 The Quantum Group $SL_h(2)$ and it’s quantum De Rham Complex

The quantum group $SL_h(2)$ is defined as a unital Hopf algebra generated by the elements of a quantum matrix

$$T = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

subject to the following relations.

$$[c, a] = hc^2 \quad [b, a] = h(1 - a^2)$$
$$[c, d] = hc^2 \quad [b, d] = h(1 - d^2)$$
$$[a, d] = h(a - d)c \quad [c, b] = h(ac + cd)$$

with the h-determinant $D_h(T) = ad - bc - hac = 1$. These relations can also be obtained from the $RTT = TTR$ relations for the following $R$-matrix.

$$R = \begin{pmatrix} 1 & h & -h & h^2 \\ 1 & 0 & h & 1 \\ 1 & -h & 1 & 1 \end{pmatrix}$$

Note that the h-determinant $D_h(T)$ is grouplike, i.e: ( for $[t_{ij}, t_{kl}] = 0$ ) : $D_h(TT') = D_h(T)D_h(T')$. The Hopf structure of $SL_h(2)$ is defined as usual:

$$\Delta T = T \otimes T$$
$$\varepsilon(T) = 1.$$  
$$S(T) = \begin{pmatrix} d - hc & -b + ha - hd + h^2c \\ c & a + hc \end{pmatrix}$$
One can also check that: if, $T \in SL_h(2)$ and $T' \in SL_{h'}(2)$, then $TT' \in SL_{h+h'}(2)$ and $S(T) \in SL_{-h}(2)$. This algebra has also a two parametric extension $SL_{h,h'}(2)$, which has been studied in ref. [20]. For the dual Algebra, that’s $U_h(sl(2))$ see [12]. It’s also interesting to note that this quantum group can be understood as a ”Quantum automorphism group” [13-14] of a pair of noncommutative linear spaces defined by the relations:

$$xy - yx = -hy^2$$

$$\xi^2 = -h\xi\eta \quad \eta^2 = 0 \quad \xi\eta + \eta\xi = 0$$

where $\xi = \hat{d}x$ and $\eta = \hat{d}y$ In Ref. [13], the complete structure of the differential graded algebra of these quantum planes together with the structure of the quantum de Rham Complex of the group itself has been studied. Here we give a brief account of this part of [13]. One starts from the ansatz

$$R_{12}\hat{d}T_1T_2 = T_2\hat{d}T_1R_{12} \quad (2)$$

the consistency of which with the defining relations (1), is due to a nice property of the $R$–matrix, namely

$$R_{12}R_{21} = R_{21}R_{12} = 1 \quad (3)$$

where $R_{21} = PR_{12}P$ and $P$ is the permutation matrix . Using this property one finds from (2) that:

$$R_{12}^{-1}\hat{d}T_2T_1 = T_1\hat{d}T_2R_{12}^{-1} \quad (4)$$

combination of (2) and (4) leads to

$$\hat{d}(R_{12}T_1T_2 - T_2T_1R_{12}) = 0 \quad (5)$$

which proves the consistency of the ansatz (2). If one then defines the left invariant one-forms as:

$$\Omega = S(T)\hat{d}T \quad (6)$$

one will obtain:

$$\Omega_1T_2R_{21} = T_2R_{21}\Omega_1 \quad (7)$$

$$\Omega_1R_{12}\Omega_2R_{21} + R_{21}\Omega_2R_{21}\Omega_1 = 0 \quad (8)$$

$$\hat{d}\Omega + \Omega \wedge \Omega = 0 \quad (9)$$
In [13], the explicit relations are derived for the matrix $\Omega$ in the form

$$\Omega = \begin{pmatrix} \frac{w_+ + w_-}{2} & u \\ v & \frac{w_+ - w_-}{2} \end{pmatrix}$$

(10)

However the relations of [13] are true for $GL_h(2)$. To obtain the corresponding relations for $SL_h(2)$ one demands that

$$\hat{d}(1) = \hat{d}(ad - bc - hac) = 0$$

For the $SL-q(2)$ quantum group one can not impose such a relation, since the determinant is not central in the differential algebra. It is only central in the algebra itself. However one can easily verify that in the $SL_h(2)$ quantum group the determinant is central in the whole differential algebra. A simple calculation shows that this puts the following restriction on the left invariant one forms:

$$w_+ = 2hv$$

which reduces the independent number of one-forms to three as expected. In terms of the indep forms $w_-, u$ and $v$, the results of solution of (7) and (8) are as follow: From (7):

$$w_-a = aw_- + 2hav \quad \quad va = av$$

(11)

$$w_-b = bw_- - 2hbv \quad \quad vb = bv + 2hav$$

(12)

$$w_-c = cw_- + 2hcv \quad \quad vc = cv$$

(13)

$$w_-d = dw_- - 2hdv \quad \quad vd = dv + 2hcv$$

(14)

$$ua = au - ha(w_- + hv)$$

(15)

$$ub = bu - 2ha(u - h^2v) + hb(w_- - hv)$$

(16)

$$uc = cu - hc(w_- + hv)$$

(17)

$$ud = du - 2hc(u - h^2v) + hd(w_- - hv)$$

(18)

From (8):

$$v \wedge v = w_- \wedge w_- = [w_-, v]_+ = 0$$

$$[u, v]_+ = h[v, w_-] \quad \quad [u, w_-]_+ = 2h[u, v]_-$$

(19)
\[ u \wedge u = h[w_-, u - 2h^2v]_- \]

where \([\alpha, \beta]_\pm \equiv \alpha \wedge \beta \pm \beta \wedge \alpha\). Note that the 2-forms \(u \wedge v, w_- \wedge v\) and \(w_- \wedge u\) span the space of 2-forms. Taking this into account eq. (9), leads to:

\[
dw_- + 2u \wedge v + 2hw_- \wedge v = 0
\]

\[
du + w_- \wedge u - 4h^2w_- \wedge v - 2hu \wedge v = 0 \quad \text{(20)}
\]

\[
dv - w_- \wedge v = 0
\]

From equation (6) one obtains \(\hat{\mathcal{T}} = T\omega\), inserting from equation (10) the form of \(\omega\) and taking into account the constraint \(w_+ = 2hv\) gives the definition of the differentials \(\hat{\partial}_{a}, ..., \hat{\partial}_{d}\) in terms of the left invariant one forms:

\[
\hat{\partial}_{a} = (b + ha)v + \frac{a}{2}w_-
\]

\[
\hat{\partial}_{b} = au + hv - b \frac{2}{w_-}
\]

\[
\hat{\partial}_{c} = (hc + d)v + \frac{c}{2}w_-
\]

\[
\hat{\partial}_{d} = cu + hdv - d \frac{2}{w_-}
\]

In the next section we combine the above results and the general construction of [17] to construct a bicovariant differential geometry on \(SL_h(2)\).

### 3 Bicovariant Differential Geometry of \(SL_h(2)\)

Let A be a Hopf algebra (here \(Fun_h(SL(2))\), briefly \(SL_h(2)\)). \(\Gamma\) an A-bimodule, i.e: the space of quantum one forms (here span \(\{\hat{\partial}_{a}, ..., \hat{\partial}_{d}\}\)), \(\Gamma_{\text{inv}}\) the space of left invariant 1-forms (here span \(\{w_i = w_1, u, v\}\)), and finally \(\Gamma_{\text{inv}}\), the space of right invariant 1-forms. Let \(\Delta_L: \Gamma \to A \otimes \Gamma\) and \(\Delta_R: \Gamma \to \Gamma \otimes A\) be the quantum analogue of the pullback of one forms under left and right multiplication of the group:

\[
\Delta_L(ab) = \Delta(a)(id \otimes d)\Delta b
\]

\[
\Delta_R(ab) = \Delta(a)(d \otimes id)\Delta b
\]

Then the following relations hold [17].

\[
\Delta_Lw_i = 1 \otimes w_i
\]
\[ \Delta_R w_i = w_j \otimes M^j_i \] (24)

The elements \( M^j_i \) then define the adjoint representation of the quantum group. As shown by Woronowicz [17] there exists functionals \( f^i_j \) and \( \chi_i \) such that:

\[ w^i a = (id \otimes f^i_j) \Delta(a) w^j \] (25)
\[ d a = (id \otimes \chi_i) \Delta(a) w^i \] (26)

Here \( f^i_j \) and \( \chi_i \) are linear maps from A to the field over which A is defined. The functionals \( f^i_j \)'s characterize the noncommutativity of the algebra, and \( \chi_i \)'s are the quantum analog of left-invariant vector fields. One can also prove that:

\[ d w^i + C^i_{jk} w^j \otimes w^k = 0 \] (27)

where \( C^k_{ij} = \chi_j(M^k_i) \). The wedge product is constructed using the quantum analog of the flip automorphism: \( \Lambda(w^i \otimes w^j) = \Lambda^{ij}_{kl} w^k \otimes w^l \):

\[ w^i \wedge w^j = w^i \otimes w^j - \Lambda^{ij}_{kl} w^k \otimes w^l \] (28)

Where

\[ \Lambda^{ij}_{kl} = f^i_j(M^k_l) \] (29)

For brevity we do not give the explicit form of the elements \( M^i_k \). They are need only in the calculation of the coefficients \( \Lambda^{ij}_{kl} \). The result of this calculation will be given later.

The Lie algebra of vector fields is defined by the following relations:

\[ \chi_i \chi_j - \Lambda^{kl}_{ij} \chi_k \chi_l = C^k_{ij} \chi_k \] (30)

for the Hopf structure of \( \chi_i, f^i_j \) and \( M^i_l \) see [17,19]. Having at our disposal the structure of the quantum De Rham Complex of \( SL_h(2) \) (Section (2)) we next apply the above formalism to it, and obtain, all the other objects characterizing the geometry of \( SL_h(2) \).

### 3.1 Vector fields and the functionals \( f^i_j \)

From eqs- ((20-b)-(20-e)) and (26) we obtain the following evaluations, for \( \chi_u, \chi_v \) and \( \chi_- \).

\[ < \chi_u, T > = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad < \chi_v, T > = \begin{pmatrix} h & 0 \\ 1 & h \end{pmatrix} \quad < \chi_-, T > = \frac{1}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \]
Similarly from eqs. (18) and (25) we obtain:

\[ \langle f^-, T \rangle = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \]

\[ \langle f^\nu, T \rangle = \begin{pmatrix} 1 & 2h \\ 0 & 1 \end{pmatrix} \]

\[ \langle f^u, T \rangle = \begin{pmatrix} 1 & -2h \\ 0 & 1 \end{pmatrix} \]

\[ \langle f^\nu, T \rangle = h^2 \begin{pmatrix} -1 & 2h \\ 0 & -1 \end{pmatrix} \]

and: \( \langle f^j, T \rangle = 0 \) for \( f^j = f^u, f^\nu, f^\nu \)

### 3.2 Tensor product realization of the wedge

A straightforward but lengthy calculation (using eq.(29)) gives the coefficients \( \Lambda^{ij}_{kl} \), as follows:

\[
\begin{align*}
\Lambda^{\alpha\beta}_{\beta\alpha} &= 1 \quad \forall \alpha, \beta \\
\Lambda^{uu}_{uu} &= -\Lambda^{uu}_{-u} = \Lambda^{uv}_{-v} = -\Lambda^{vu}_{-v} = -2h \\
\Lambda^{v\nu}_{v\nu} &= \Lambda^{v\nu}_{-v} = -\Lambda^{v\nu}_{-v} = -4h \\
\Lambda^{uu}_{vv} &= \Lambda^{uu}_{vv} = \Lambda^{uu}_{-u} = \Lambda^{uu}_{-v} = \Lambda^{-u}_{-v} = -4h^2 \\
\Lambda^{u_{-v}} &= -\Lambda^{v_{-u}} = -8h^3
\end{align*}
\]

and all others equal to zero.

This then gives via eq.(28) the following tensor product realization for the wedge product.

\[
\begin{align*}
\mathbf{u} \wedge \mathbf{u} &= 2h \left( \mathbf{w}_- \otimes \mathbf{u} - \mathbf{u} \otimes \mathbf{w}_- + 2h(\mathbf{u} \otimes \mathbf{v} + \mathbf{v} \otimes \mathbf{u}) \right) \\
\mathbf{u} \wedge \mathbf{v} &= \mathbf{u} \otimes \mathbf{v} - \mathbf{v} \otimes \mathbf{u} + 2h\mathbf{v} \otimes \mathbf{w}_- + 4h^2 \mathbf{v} \otimes \mathbf{v} \\
\mathbf{u} \wedge \mathbf{w}_- &= \mathbf{u} \otimes \mathbf{w}_- - \mathbf{w}_- \otimes \mathbf{u} - 4h\mathbf{v} \otimes \mathbf{u} + 4h^2(\mathbf{v} \otimes \mathbf{w}_- + 2h\mathbf{v} \otimes \mathbf{v}) \\
\mathbf{v} \wedge \mathbf{u} &= \mathbf{v} \otimes \mathbf{u} - \mathbf{u} \otimes \mathbf{v} - 2h(\mathbf{w}_- \otimes \mathbf{v} - 2h\mathbf{v} \otimes \mathbf{v}) \\
\mathbf{v} \wedge \mathbf{v} &= 0 \\
\mathbf{v} \wedge \mathbf{w}_- &= \mathbf{v} \otimes \mathbf{w}_- - \mathbf{w}_- \otimes \mathbf{v} + 4h\mathbf{v} \otimes \mathbf{v}
\end{align*}
\]
\[
\begin{align*}
\mathbf{w}_- \wedge \mathbf{u} &= \mathbf{w}_- \otimes \mathbf{u} - \mathbf{u} \otimes \mathbf{w}_- + 4h \mathbf{u} \otimes \mathbf{v} + 4h^2(\mathbf{w}_- \otimes \mathbf{v} - 2h \mathbf{v} \otimes \mathbf{v}) \\
\mathbf{w}_- \wedge \mathbf{v} &= \mathbf{w}_- \otimes \mathbf{v} - \mathbf{v} \otimes \mathbf{w}_- - 4h \mathbf{v} \otimes \mathbf{v} \\
\mathbf{w}_- \wedge \mathbf{w}_- &= 0
\end{align*}
\]

One can now check the associativity of the wedge product, the commutation relations (19) and the validity of Liebnitz rule: i.e : \( d(\alpha \wedge \beta) = (d\alpha) \wedge \beta + (-1)^{\deg\alpha} \alpha \wedge d\beta, \forall \alpha, \beta \in \mathcal{A} \oplus \mathcal{\Gamma} \)

### 3.3 The h-Lie algebra of the vector Fields

To obtain the structure constants \( C_{ij}^k \) we insert the above realization of the wedge product in equation (20) and then use (27). The result is:

\[
C_{u-}^u = -C_{u-}^u = C_{v-}^v = -C_{v-}^v = \frac{1}{2}C_{uv} = \frac{-1}{2}C_{vu} = 1
\]

\[
C_{uv}^u = C_{vu}^u = C_{v-}^v = C_{v-}^v = \frac{1}{2}C_{vv} = 2h
\]

and all others equal to zero.

Eq.(30) will then give the following h-Lie algebra for the vector fields:

\[
\begin{align*}
[\chi_-, \chi_u] &= (1 - 2h\chi_u)\chi_u \\
[\chi_-, \chi_v] &= -(1 - 2h\chi_u)(\chi_v + 2h\chi_-) \\
[\chi_u, \chi_v] &= -2(1 - 2h\chi_u)(h\chi_u - \chi_-)
\end{align*}
\]

One can check the Jacobi identity for this deformed Lie algebra. Obviously this algebra goes to the Lie algebra of \( \mathfrak{sl}(2) \) in the limit \( h \to 0 \).

### 3.4 Lie derivative of Left-invariant forms

The Lie derivative of one forms along left invariant vector fields is defined as

\[
L_{\chi_i}w_j = (id \otimes \chi_i)\Delta_R w_j
\]

from which we obtain:
\[
\begin{align*}
L_{\chi^a} \begin{pmatrix} u \\ v \\ w_- \end{pmatrix} &= \begin{pmatrix} w_- + 2hv \\ 0 \\ -2v \end{pmatrix} & L_{\chi^v} \begin{pmatrix} u \\ v \\ w_- \end{pmatrix} &= \begin{pmatrix} 2hu \\ -w_- + 4hv \\ 2u + 2hw_- \end{pmatrix} \\
L_{\chi^-} \begin{pmatrix} u \\ v \\ w_- \end{pmatrix} &= \begin{pmatrix} -u \\ v \\ 2hv \end{pmatrix}
\end{align*}
\]

It’s easy to see that these Lie derivatives, actually represent the h-Lie algebra (32). i.e:

\[
L_{\chi^i}L_{\chi^j} - \Lambda_{ij}^{kl}L_{\chi^k}L_{\chi^l} = C_{ij}^kL_{\chi^k}
\]

4 A new deformation of $sl_2$ Lie algebra

As it stands eqs. (32) define a deformation of the Lie algebra of $sl(2)$. However the form of these equations can be put into a more symmetrical form by the following redefinitions. Set:

\[
J_0 \equiv \chi_- \quad J_+ \equiv \chi_u \quad J_- \equiv \chi_v + h^2\chi_u
\]

Then after some symmetrizations one gets:

\[
\begin{align*}
[J_0, J_+] &= \frac{1}{2}(KJ_+ + J_+K) \\
[J_0, J_-] &= -\frac{1}{2}(KJ_- + J_-K) \\
[J_+, J_-] &= KJ_0 + J_0K
\end{align*}
\]

where $K = 1 - 2hJ_+$. This algebra is then a new deformation of the $sl(2)$ Lie algebra.

The matrices

\[
J_0 = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & -\frac{1}{2} \end{pmatrix} \quad J_+ = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \quad J_- = \begin{pmatrix} h & h^2 \\ 1 & h \end{pmatrix}
\]

form a two-dimensional representation of this algebra.

It’s interesting to note that this algebra has indeed a Casimiar operator given by:
\[ C = J_+ J_- + J_- J_+ + 2J_0^2 + \frac{1}{2}K^2 \]  

(34)

Note that all the deformation is effected by the element \( K \) which is linear in the generators. One can also derive the commutation relations of \( K \) with the other elements:

\[
[J_+, K] = 0
\]

\[
[J_0, K] = -h(KJ_+ + J_+K)
\]

(35)

\[
[J_-, K] = 2h(KJ_0 + J_0K)
\]

If one then treats \( K \) as an independent generator, the relations (33) and (35) define a deformation of the Lie algebra of \( gl(2) \).

It may be interesting to study the representation of the algebra (33) and to see if as in the \( sl_q(2) \) case, it parallels those of the classical Lie algebra \( sl(2) \) for generic values of \( h \) and if it shows peculiarities for some specific values of the deformation parameter.

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