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The Applications of the Superconformal Transformation in the Integrable Models

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We show that superconformal $N = 2$ transformation could be applied to the construction of the supersymmetric analogon of the reciprocal transformation. Due to it we present the connections between three different $N = 2$ supersymmetric extensions of the Korteweg de Vries equations with the three different $N = 2$ supersymmetric extension of the Harry Dym equation.

Keywords: *superconformal transformation, Lax representation, supersymmetric Korteweg de Vries and Harry Dym equation.*

1 Introduction

The reciprocal transformation, also known as hodograph transformation, plays an important role when we investigate relations among some nonlinear evolution equations [1] . For instance, the Harry Dym (HD) equation (or hierarchy), which is invariant under a kind of reciprocal transformation, is also reciprocally linked to the Korteweg-de Vries (KdV) equation (or hierarchy).

Very recently, the reciprocal transformation was generalized to N = 1 supersymmetric equations, where a general procedure to construct supersymmetric reciprocal transformation was presented [2] . It appeared that this transformation is connected with the superconforaml transformation [3] .

As applications, one of the supersymmetric HD equations was shown to be reciprocally linked to the supersymmetric modified KdV equation. This supersymmetric modified KdV equation is connected via the Miura transformation with the supersymmetric KdV equation.

As in the classical case, the supersymmetric reciprocal transformation could be employed to explore integrable properties of supersymmetric equations, which was illustrated by constructing the recursion operators and bi-Hamiltonian structures of the supersymmetric Harry Dym equation.

Besides N = 1 supersymmetric generalizations, the integrable systems also admit N = 2 extended supersymmetric generalizations [4–10]. The idea could almost be traced back to the usage of the supersymmetry in the quantum field theory. As a striking feature, N=2 extended case distinguishes itself from N = 1 non-extended case by the possibility to supply new classical integrable systems. The N = 2 supersymmetric KdV equations were proposed more than twenty years ago and have been studied extensively since then. Various results for these equations have been obtained, including Lax representations, bi-Hamiltonian structures, bilinear formalism, and so on.

Very recently three different supersymmetric $N = 2$ of the Harry Dym equation have been also proposed. In this paper we show how these supersymmetric equations are connected each other by teh superconformal transformation.

The paper is organised as follow. In the second section we briefly recapitulate basic facts on the $n = 1, 2$ superconformal transformation. In the third section we disccuss the properties of the classical Harry Dym equation and explain how this equation is connected with the KdV equation. Fourth section constains the descriptions of the supersymmetrical $N = 2$ kdV and HD equations. In the fifth sections the connection of the $N = 2$ supersymmetric Harry Dym equations with the $N = 2$ KdV equation is presented. The last section contains concluding remarks.

2 N=1,2 superconformal transformation

The conformal map means a function which preserves angles. It is a general definition of conformal transformation.

The supersymmetric analogon of the conformal map could be constructed using the superconformnal transformations. From the technical reasons we distinguish two cases of the supersymmetry: the $N = 1$and $N = 2$ independently

A.) $N = 1$ superconformal transformation.

In order to construct the super covariant operators let us consider the super diffeomorphism $N = 1$ in which we change [3]

$$\begin{aligned} X &= (x, \theta) \Rightarrow Z = (z, \gamma) = (z(x, \theta, \gamma(x, \theta)) \qquad (1) \\ \mathcal{D} &= \theta\partial_x + \partial_\theta \qquad \hat{\mathcal{D}} = \gamma\partial_z + \partial_\gamma \end{aligned}$$

Due to it one finds

$$\mathcal{D} = (\mathcal{D}\gamma)\hat{\mathcal{D}} + [(\mathcal{D}z) - \gamma(\mathcal{D}\gamma)]\partial_z \qquad (2)$$

We assume that $\mathcal{D}$ should transforms covariantly. It means that

$$\mathcal{D} \;\Rightarrow\; \hat{\mathcal{D}} = (\mathcal{D}\gamma)^{-1}\mathcal{D} \;\Rightarrow\; (\mathcal{D}z) = \gamma(\mathcal{D}\gamma) \qquad (3)$$

It is a superconformal transformation.

Example: Super Hill operator

$$\mathcal{D}^3 + \Phi(X) \Rightarrow \hat{\mathcal{D}}^3 + \Phi(\mathcal{D}\gamma)^{-2}(\mathcal{D}^3 + \hat{\Phi})(\mathcal{D}\gamma)^{-1} \qquad (4)$$

Assuming the infinitesimal form of this transformation as

$$\begin{aligned} z(x,\theta) &= x + e(x,\theta), \\ \gamma(x,\theta) &= \theta + \lambda(x,\theta) \end{aligned} \qquad (5)$$

we obtain that

$$\begin{aligned} \Phi(Z) &= \Phi(X) + \lambda(\mathcal{D}\Phi) + (E := e + \theta\lambda)\Phi_x + \dots \\ \delta_E\Phi(X) &= \frac{1}{2}\Big(\mathcal{D}^5 + 3\Phi\partial + (\mathcal{D}\Phi)\mathcal{D} + 2\Phi_x\Big)E(X) \end{aligned} \qquad (6)$$

From the last equation we obtain the following representation of the N=1 Virasoro algebra

$$\{\Phi(Z), \Phi(\hat{Z})\} = (\mathcal{D}^5 + 3\Phi\partial + (\mathcal{D}\Phi)\mathcal{D} + 2\Phi_x)\delta(x-\hat{x})(\theta-\hat{\theta}) \qquad (7)$$

B.) $N = 2$ superconformal transformation [3]

The super diffeomorphism between (x, θ_1, θ_2) and $(y, \varrho_1, \varrho_2)$.

$$y \Rightarrow x = x(y, \varrho_1, \varrho_2), \qquad \varrho_i \Rightarrow \theta_i = \theta_i(y, \varrho_1, \varrho_2), \qquad (8)$$

where $i = 1, 2$. The superderivatives are

$$\mathbb{D}_k = \partial_{\varrho_k} + \varrho_k\partial_y, \qquad \mathcal{D}_k = \partial_{\theta_k} + \theta_k\partial_x, \qquad (k = 1,2) \qquad (9)$$

Computing $\mathbb{D}_k$ we have

$$\mathbb{D}_k = \Big((\mathbb{D}_k x) - \theta_i(\mathbb{D}_k\theta_i)\Big)\partial_x + (\mathbb{D}_k\theta_i)\mathcal{D}_i \qquad (10)$$

where the summation on the repeated index i is assumed.

To ensure that the superderivatives transform covariantly i.e. $\mathbb{D}_k = (\mathbb{D}_k\theta_i)\mathcal{D}_i$ we have to assume the constraints

$$(\mathbb{D}_k x) = \theta_i(\mathbb{D}_k\theta_i) \qquad (11)$$

Moreover to ensure that $\mathcal{D}_k^2 = \partial_x, (k = 1, 2)$ we have assume also

$$(\mathbb{D}_1\theta_2) = -(\mathbb{D}_2\theta_1), \qquad (\mathbb{D}_2\theta_2) = (\mathbb{D}_1\theta_1) \qquad (12)$$

Hence we have

$$\begin{aligned} \mathcal{D}_1 &= K^{-1}\Big(\;(\mathbb{D}_1\theta_1)\mathbb{D}_1 + (\mathbb{D}_2\theta_1)\mathbb{D}_2\Big) \\ \mathcal{D}_2 &= K^{-1}\Big(-(\mathbb{D}_2\theta_1)\mathbb{D}_1 + (\mathbb{D}_2\theta_1)\mathbb{D}_2\Big) \end{aligned} \qquad (13)$$

where $K = (\mathbb{D}_1\theta_1)^2 + (\mathbb{D}_2\theta_1)^2$. In fact we obtain

$$\begin{aligned} \mathcal{D}_1\mathcal{D}_2 &= K^{-1}\Big[1 + 2\Gamma - \mathbb{D}_i\Gamma\partial_y^{-1}\mathbb{D}_i\Big]\mathbb{D}_1\mathbb{D}_2 \\ \partial_x &= K^{-1}\Big[1 + 2\Gamma - \mathbb{D}_i\Gamma\partial_y^{-1}\mathbb{D}_i\Big]\partial_y \end{aligned} \qquad (14)$$

where $\Gamma = \log(K)/2$. Based on them we can prove

$$\partial_x^{-1}\mathcal{D}_1\mathcal{D}_2 = \partial_y^{-1}\mathbb{D}_1\mathbb{D}_2 \qquad (15)$$

The two last formulas we will use extensively in the next sections.

3 Harry Dym Equation

The Harry Dym equation usually is written in three different but equivalent forms

$$w_t = (\frac{1}{\sqrt{w}})_{xxx}, v_t = \frac{1}{4}v^3 v_{xxx}, u_t = (\frac{1}{\sqrt{u_{xx}}})_x \qquad (16)$$

where

$$v = -2^{1/3}\frac{1}{\sqrt{w}}, \qquad w = u_{xx} \qquad (17)$$

This equation is integrable and possesses the following Bi-Hamiltonian structure

$$w_t = \mathcal{J}_1\frac{\delta H_{-1}}{\delta w} = \mathcal{J}_2\frac{\delta H_{-2}}{\delta w} \qquad (18)$$

where

$$H_{-1} = 2\int dx\;\sqrt{w}, \quad H_{-2} = \frac{1}{8}\int dx\; w^{-1/5}w_x^2 \qquad (19)$$

$$\mathcal{J}_1 = \partial_{xxx}, \qquad \mathcal{J}_2 = \partial w + w\partial \qquad (20)$$

The Harry Dym equation could be obtained from the so called standard or nonstandard Lax representation in a similar manner as for the KdV equation. The Lax representation plays an important role in the theory of integrable systems, because a lot of informations on the properties of the equations follows from these representations. In order to construct such representations for HD equation let us consider first the standard and nonstandard Lax representation of the Korteweg de Vries equation

$$w_t = w_{xxx} + 6ww_x \qquad (21)$$

The Standard representation of KdV equation is

$$L_s = w + \partial_{xx}, \quad L_{s,t} = [(L_s^{3/2})_{\geq 0}, L_s], \qquad (22)$$

while the nonstandard representation

$$L_{ns} = \partial + \partial^{-1}w, \quad L_{ns,t} = [(L_{ns}^3)_{\geq 1}, L_{ns}], \qquad (23)$$

Now let us establish the reciprocal link between KdV ⇔ HD. This link could be formulated in three steps: first is to use a gauge transformation of the Lax operator, in the second step we apply the Miura transformation and in the last step we apply the reciprocal transformation

A.) Standard Lax operator:

I.) Gauge transformation

$$\hat{L}_s = e^{\int v} L_s e^{-\int v} = \partial_{xx} - 2v\partial_x + u - v_x + v^2 \qquad (24)$$

II.) Miura transformation

$$u = v_x - v^2, \qquad \hat{L}_s = \partial_{xx} - 2v\partial_x \qquad (25)$$

III.) Reciprocal

$$y = \omega(x,t), t' = t, \partial_x = \omega_x \partial_y \qquad (26)$$

$$\hat{L}_s = \omega^2 \partial_{yy} + (\omega_x - 2v\omega)\partial_y \qquad (27)$$

where $v = \frac{\omega_x}{2\omega}$

B.) Nonstandard Lax operator:

I.) Gauge transformation

$$\hat{L}_{ns} = \phi^{-1} L_{ns} \phi = \phi^{-1}\partial_x^{-1}\phi\ (\partial_{xx} + 2\phi_x\phi^{-1}\partial_x + \phi_{xx}\phi^{-1} + u) \qquad (28)$$

II.) Analogon of Miura transformation

$$\phi = \frac{1}{\sqrt{\omega}}, \quad u = \frac{1}{2}\omega_{xx}\omega^{-1} - \frac{3}{4}\omega_x^2\omega^{-1} \qquad (29)$$

$$\hat{L}_{ns} = \sqrt{\omega}\partial^{-1}\frac{1}{\sqrt{\omega}}\ (\partial_{xx} - \omega_x\omega^{-1}\partial_x)$$

III.) Reciprocal Transformation

Let us notice

$$\frac{\partial}{\partial\tau}\hat{L}_{ns} = \Big[B\ ,\ \hat{L}_{ns}\Big], \qquad (30)$$

$$B = \partial_{xxx} - \frac{3}{2}\omega_x\omega^{-1}\partial_{xx},$$

$$\omega_\tau = \partial_x(\omega_{xx} - \frac{3}{2}\omega_x^2\omega^{-1})$$

Therefore

$$dy = \omega dx + (\omega_{xx} - \frac{3}{2}\omega_x^2\omega^{-1})d\tau, d\tau = dt \qquad (31)$$

$$\frac{\partial}{\partial y} = \omega\frac{\partial}{\partial_y}, \frac{\partial}{\partial\tau} = \frac{\partial}{\partial t} + (\omega_{xx} - \frac{3}{2}\omega_x^2\omega^{-1})\frac{\partial}{\partial y}$$

We obtain

$$\omega_t = \omega^3\omega_{yyy}, \hat{L}_{ns} = \sqrt{\omega}\partial^{-1}\sqrt{\omega}\partial_{yy} \qquad (32)$$

4 Supersymmetric N=2 extensions of KdV and HD equations

A.) Supersymmetric $N = 2$extensions of KdV equation [3, 10, 11]

We meet three different $N = 2$ supersymmetric extensions of the KdV equation which could be written in compact for as

$$U_t = (-U_{xx} + 3UD_1D_2U + \frac{(a-1)}{2}D_1D_2U + aU^3)_x.$$

where $a = 4, -2, 1$ and

$$D_1 = \frac{\partial}{\partial\theta_1} = \theta_1\partial_x, \quad D_2 = \frac{\partial}{\partial\theta_2} + \theta_2\partial_x \qquad (33)$$

The bosonic part in which we assume that $U = w + \theta_1\theta_2 u$ gives us

$$w_t = (-w_{xx} + aw^3 + (a+2)uw)_x \qquad (34)$$

$$u_t = (-u_{xx} + 3u^2 - (a-1)w_x^2 - (a+2)ww_{xx} + 3auw^2)_x$$

the system of interacted equations. From that reasons the applications of the extended supersymmetry to integrable systems could be considered as the method of the extensions of new integrable systems.

Let us now consider the Lax representations for these three supersymmetric extensions.

1.) $a = 4$

$$L_4 = -(D_1D_2 + U)^2, \quad L_{4,t} = 4\ [L^{3/2}_{4,\geq 0}\ ,\ L_4] \qquad (35)$$

$$U_t = (-U_{xx} - 3(D_1U)(D_2U) + 6(D_1D_2U)U + 4U^3)_x \qquad (36)$$

2.) $a = -2$

$$L_{-2} = L_{4,\geq 1}, \quad L_{-2,t} = 4\ [L^{3/2}_{-2,\geq 0}\ ,\ L_{-2}] \qquad (37)$$

$$U_t = (-U_{xx} - 3(D_1U)(D_2U) - 2U^3)_x \qquad (38)$$

3.) $a = 1$

$$L_1 = \partial + \partial^{-1}D_1D_2U, \quad L_{1,t} = [L, L^3_{1,\geq 1}] \qquad (39)$$

$$U_t = (-U_{xx} - 3U(D_1D_2U) + U^3)_x \qquad (40)$$

B.) Supersymmetric N=2 Harry Dym equation and its Lax operators $a = 4,\ -2,\ 1$ [5, 12, 13].

In a similar manner to supersymmetric KdV equation we have three different supersymmetric $N = 2$ extensions of the Harry Dym equation. We enumerate these equations using the same free parameter a as in the supersymmetric KdV cases. This enumerating system will be explained in the next section.

1.) $a = 4$

$$L_4 = -(\omega D_1D_2)^2, \quad L_{4,t} = [L^{3/2}_{4,\geq 2}\ ,\ L_4] \qquad (41)$$

$$\omega_t = \frac{1}{8}(2\omega_{xxx}\omega^3 - 6(D_1D_2\omega_x)(D_1D_2\omega)\omega^2 - 3(D_1\omega_{xx})(D_1\omega)\omega^2 - 3(D_2\omega_{xx})(D_2\omega)\omega^2)$$

2.) $a = -2$

$$L_{-2} = \frac{1}{2}(D_1\omega^2 D_1 + D_2\omega^2 D_2)\partial_x \quad (42)$$

$$\omega_t = \frac{1}{8}(2\omega_{xxx}\omega^3 - 3(D_1D_2\omega_x)(D_1D_2\omega)\omega^2 - 3(D_1\omega_{xx})(D_1\omega)\omega^2 + 3(D_2\omega_{xx})(D_2\omega)\omega^2$$

3.) $a = 1$

$$L_1 = \sqrt{\omega}\partial^{-1}D_1D_2\sqrt{\omega}D_1D_2 \quad (43)$$

$$\omega_t = \frac{1}{4}(4\omega^3\omega_{xxx} - 6(D_1D_2\omega_x)(D_1D_2\omega)\omega^2 - 6(D_1\omega_{xx})(D_2\omega)\omega^2 - 6(D_1\omega_{xx})(D_1\omega)\omega^2 + 3(D_2\omega)(D_1\omega)(D_1D_2\omega_x)\omega)$$

5 Supersymmetricl reciprocal link between supersymmetric HD and supersymmetric KdV

[2, 13]

I.) a=4.

Let us rewrite the Lax operator

$$L_4 = -(\omega\mathcal{D}_1\mathcal{D}_2)^2 \quad (44)$$

in the new variables 13 we obtain

$$\hat{L}_4 = -\big[\mathbb{D}_1\mathbb{D}_2 + (\mathbb{D}_2\mathit{\Gamma})\mathbb{D}_1 - (\mathbb{D}_1\mathit{\Gamma})\mathbb{D}_2\big]^2 \quad (45)$$

$$\mathit{\Gamma} = \log(K)/2, \qquad K = \omega$$

Applying the gauge transformation

$$\hat{\mathcal{L}}_4 = e^{-\mathit{\Gamma}}\hat{L}_4 e^{\mathit{\Gamma}} = -\big[\mathbb{D}_1\mathbb{D}_2 + (\mathbb{D}_1\mathbb{D}_2\mathit{\Gamma}) + (\mathbb{D}_2\mathit{\Gamma})(\mathbb{D}_1\mathit{\Gamma})\big]^2 \quad (46)$$

we obtained the Lax operator which gives us the supersymmetrical $MKdV_4$ equation via

$$\hat{\mathcal{L}}_{4,t} = [(\hat{\mathcal{L}}_4)^{3/2}_{\geq 1}, \hat{\mathcal{L}}_4] \quad (47)$$

The obtained equation is connected with the supersymmetric KdV_4 by the following supersymmetric Miura transformation

$$\Phi = (\mathbb{D}_1\mathbb{D}_2\mathit{\Gamma}) + (\mathbb{D}_2\mathit{\Gamma})(\mathbb{D}_1\mathit{\Gamma})$$

II.) a=-2.

If we rewrite the Lax operator

$$L_{-2} = \frac{1}{2}\big(\mathcal{D}_1\omega^2\mathcal{D}_1 + \mathcal{D}_2\omega^2\mathcal{D}_2\big)\partial_x \quad (48)$$

in the new variables 13 and using the gauge transformation we obtain

$$\hat{L}_{-2} = e^{-\mathit{\Gamma}}\hat{L}_4 e^{\mathit{\Gamma}} = \quad (49)$$

$$\partial_{yy} - \mathit{\Gamma}_y - \frac{1}{2}(\mathbb{D}_2\mathit{\Gamma}_y)(\mathbb{D}_1\mathit{\Gamma})\mathbb{D}_1\mathbb{D}_2 + \frac{1}{4}\big(-2(\mathbb{D}_2\mathit{\Gamma}_y) + (\mathbb{D}_2\mathit{\Gamma}_y) - (\mathbb{D}_1\mathit{\Gamma})(\mathbb{D}_1\mathbb{D}_2\mathit{\Gamma})\big)\mathbb{D}_2 + \frac{1}{4}\big(-2(\mathbb{D}_1\mathit{\Gamma}_y) + (\mathbb{D}_1\mathit{\Gamma}_y) - (\mathbb{D}_2\mathit{\Gamma})(\mathbb{D}_1\mathbb{D}_2\mathit{\Gamma})\big)\mathbb{D}_1 \quad (50)$$

where $\omega = e^{\mathit{\Gamma}}$, that $\hat{L}_{-2}$ operator generates the supersymmetric $MKdV_{-2}$ equation via

$$\hat{L}_{-2,t} = \big[\hat{L}^{3/2}_{-2,\geq 1}\ ,\ \hat{L}_{-2}\big] \quad (51)$$

and produces the supersymmetric KdV_{-2} equation after the applications of the following supersymmetric Miura transformation

$$\Phi = \frac{1}{2}(\mathbb{D}_1\mathbb{D}_2\mathit{\Gamma}) + \frac{1}{4}(\mathbb{D}_2\mathit{\Gamma})(\mathbb{D}_1\mathit{\Gamma}) \quad (52)$$

III.) a=1.

If we rewrite the Lax operator

$$L_1 = \sqrt{\omega}\partial_x^{-1}\mathcal{D}_1\mathcal{D}_2\sqrt{\omega}\mathcal{D}_1\mathcal{D}_2 \quad (53)$$

in the new variables 13 we obtain

$$\hat{L}_1 = \sqrt{\omega}\partial_y^{-1}\mathbb{D}_1\mathbb{D}_2\sqrt{\frac{1}{\omega}}\Big[\mathbb{D}_1\mathbb{D}_2 + \quad (54)$$

$$\frac{1}{2\omega}(\mathbb{D}_2\omega)\mathbb{D}_1 - \frac{1}{2\omega}(\mathbb{D}_1\omega)\mathbb{D}_2\Big] \quad (55)$$

After application of the gauge transformation

$$\mathcal{L}_1 = \frac{1}{\sqrt{\omega}}\hat{L}_1\sqrt{\omega} = \partial_y^{-1}\mathbb{D}_1\mathbb{D}_2\Big[\mathbb{D}_1\mathbb{D}_2 + \frac{1}{2}\frac{(\mathbb{D}_1\mathbb{D}_2\omega)}{\omega} + \frac{3}{4}\frac{(\mathbb{D}_2\omega)(\mathbb{D}_1\omega)}{\omega^2}\Big] \quad (56)$$

After the identification e.g using the supersymmetrical Miura transformation

$$\Phi = \frac{1}{2}\frac{(\mathbb{D}_1\mathbb{D}_2\omega)}{\omega} + \frac{3}{4}\frac{(\mathbb{D}_2\omega)(\mathbb{D}_1\omega)}{\omega^2}$$

$\mathcal{L}_1$ is a Lax operator for the supersymmetrical KdV_1 equation.

6 Conclusion

In this paper we showed how one can adopt the superconformal transformation to the supersymmetrical integrable models. We presented it on the connections between the supersymmetrical Harry Dym equations and the supersymmetrical KdV equation. This link appeared very usefull because it simplifies the investigations of the properties of the new integrable equations.

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ПРИМЕНЕНИЕ СУПЕРКОНФОРМНЫХ ПРЕОБРАЗОВАНИЙ В ИНТЕГРИРУЕМЫХ МОДЕЛЯХ

Показано, что N=2 суперконформные преобразования могут быть применимы для построения суперсимметричного аналога обратных преобразований. С их помощью устанавливается связь между тремя различными N=2 суперсимметричными расширениями уравнений Кортевега- де Фриза и тремя различными N = 2 суперсимметричными расширениями уравнений Гарри - Дыма.

Ключевые слова: *суперконформные преобразования, представление Лакса, суперсимметричные уравнения Кортевега - де Фриза и Гарри - Дыма.*

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