Fritz Gesztesy and Helge Holden

The classical boussinesq hierarchy revisited
Editor

Harald Nissen, The Royal Norwegian Society of Sciences and Letters,
Erling Skakkes gt. 47b, 7013 Trondheim

Editorial board

Jon Lamvik, professor – Medicine/Biology
Arne Jensen, professor – Chemistry/Geology
Haakon Waadeland, professor – Physics/Mathematics
Harald A. Øye, professor – Technology
Peder Borgen, professor – Philosophy/Religion/Psychology
Per Fuglum, professor – History/Social sciences
Vacant – Literature/Languages/Art

Tapir Academic Press, 7005 Trondheim

Communications regarding accepted manuscripts, orders of reprints,
subscriptions etc. should be sent to the Publisher.
THE CLASSICAL BOUSINESQ HIERARCHY REVISITED

FRITZ GESZTESY AND HELGE HOLDEN

ABSTRACT. We develop a systematic approach to the classical Boussinesq (cBsq) hierarchy based on an elementary polynomial recursion formalism. Moreover, the gauge equivalence between the cBsq and AKNS hierarchies is studied in detail and used to provide an effortless derivation of algebro-geometric solutions and their theta function representations of the cBsq hierarchy.

1. INTRODUCTION

We develop an elementary algebraic approach to the classical Boussinesq (cBsq) hierarchy in close analogy to previous treatments of the KdV, AKNS, and Toda hierarchies (cf. [2], [9], [10], [12] and the references therein). The complete integrability of the classical Boussinesq system (and its closely related variants, also known as the Kaup-Boussinesq, Broer-Kaup, and classical Boussinesq-Burgers system),

\[ u_t + \frac{1}{4} u_{xxx} + (uw)_x = 0, \quad v_t + uv_x - u_x = 0, \]  

was originally established by Kaup [19], [20]. Various aspects of this system (and its variants) are studied, for instance, in [3], [4], [5], [8], [13], [14], [15], [18], [21], [23], [24], [25], [27], [30], [31], and [32].

Subsequently, the equivalence of the classical Boussinesq system (1.1) and the AKNS system,

\[ p_t + \frac{i}{2} p_{xx} - ip^2 q = 0, \quad q_t - \frac{i}{2} q_{xx} + ipq^2 = 0, \]  

was established by Jaulent and Miodek [18] by means of the explicit transformation

\[ u + \frac{i}{2} v = -pq, \quad v = \frac{p_x}{p} \]  

(cf. Section 4 for more details).

The principal purpose of this note is threefold. First, we develop the zero-curvature formalism of the cBsq hierarchy in Section 3 using a polynomial recursion formalism (independently of its connection with the AKNS hierarchy). Second, we provide a new and elementary proof of the gauge equivalence between the cBsq and AKNS hierarchies in Section 4. Finally, using this gauge equivalence, we derive the class of algebro-geometric solutions of the cBsq hierarchy in Section 5.

The AKNS hierarchy and its class of algebro-geometric solutions, the fundamental ingredients for Sections 4 and 5, are briefly reviewed in Section 2.

1991 Mathematics Subject Classification. Primary 35Q53, 35Q55, 58F07; Secondary 35Q31, 35Q58.

Key words and phrases. Classical Boussinesq hierarchy, AKNS hierarchy, algebro-geometric solutions, gauge equivalence.

Supported in part by the Research Council of Norway under grant 107510/410 and the University of Missouri Research Board grant RB-97-086.
2. THE AKNS HIERARCHY

In this section we review the construction of the AKNS hierarchy and its algebro-geometric solutions following a recursive approach to the AKNS zero-curvature formalism developed in [11].

We start by recalling the recursive construction of the AKNS hierarchy. Suppose $p, q : \mathbb{C} \to \mathbb{C}_\infty$ with $\mathbb{C}_\infty = \mathbb{C} \cup \{\infty\}$, are meromorphic and introduce the matrix

$$U(z, x) = \begin{pmatrix} -iz & q(x) \\ \frac{1}{p(x)} & iz \end{pmatrix}. \quad (2.1)$$

Define $\{f_\ell(x)\}_{\ell \in \mathbb{N}_0}$, $\{g_\ell(x)\}_{\ell \in \mathbb{N}_0}$, and $\{h_\ell(x)\}_{\ell \in \mathbb{N}_0}$ recursively by

$$f_0(x) = -iq(x), \quad g_0(x) = 1, \quad h_0(x) = ip(x),$$

$$f_{\ell+1}(x) = \frac{i}{2} f_{\ell, x}(x) - iz(x)g_{\ell+1}(x),$$

$$g_{\ell+1, x}(x) = p(x)f_{\ell}(x) + q(x)h_{\ell}(x),$$

$$h_{\ell+1}(x) = -\frac{i}{2} h_{\ell, x}(x) + ip(x)g_{\ell+1}(x), \quad \ell \in \mathbb{N}_0. \quad (2.2)$$

Explicitly, one finds

$$f_0 = -iq, \quad f_1 = \frac{1}{2} q_x + c_1(-iq),$$

$$f_\ell = \frac{i}{4} q_{\ell, x} - \frac{i}{2} p q_x + c_1 \left(\frac{1}{2} q_x\right) + c_2(-iq),$$

$$g_0 = 1, \quad g_1 = c_1, \quad g_2 = \frac{1}{2} pq + c_2,$$

$$g_\ell = -\frac{i}{4} (pq - p q_x) + c_1 \left(\frac{1}{2} pq\right) + c_2,$$

$$h_0 = ip, \quad h_1 = \frac{1}{2} p_x + \frac{1}{2} (ip),$$

$$h_\ell = -\frac{i}{4} p_{\ell, x} + \frac{1}{2} p q + c_1 \left(\frac{1}{2} p_x\right) + c_2 (ip),$$

etc.,

where $\{c_j\}_{j \in \mathbb{N}} \subset \mathbb{C}$ are integration constants.

Next, define the matrix $V_{n+1}(z, x)$ by

$$V_{n+1}(z, x) = \begin{pmatrix} -G_{n+1}(z, x) & F_n(z, x) \\ -H_n(z, x) & G_{n+1}(z, x) \end{pmatrix}, \quad n \in \mathbb{N}_0, \quad (2.4)$$

where $F_n(z, x)$, $G_{n+1}(z, x)$, and $H_n(z, x)$ are polynomials in $z \in \mathbb{C}$ of the type,

$$F_n(z, x) = \sum_{\ell=0}^{n} f_{n-\ell}(x) z^\ell = -iq \prod_{j=1}^{n} (z - \mu_j(x)), \quad (2.5)$$

$$G_{n+1}(z, x) = \sum_{\ell=0}^{n+1} g_{n+1-\ell}(x) z^\ell,$$

$$H_n(z, x) = \sum_{\ell=0}^{n} h_{n-\ell}(x) z^\ell = ip \prod_{j=1}^{n} (z - \nu_j(x)).$$

Using the recursion (2.2) one verifies

$$F_{n,x} = -2iz F_n + 2q G_{n+1},$$

$$G_{n+1,x} = p F_n + q H_n,$$

$$H_{n,x} = 2iz H_n + 2p G_{n+1}, \quad (2.6)$$
implying
\[(G^2_{n+1} - F_n H_n)_z = 0, \quad (2.7)\]
and hence
\[G_{n+1}(z, x)^2 - F_n(z, x) H_n(z, x) = R_{2n+2}(z), \quad (2.8)\]
where \(R_{2n+2}(z)\) is a monic polynomial of degree \(2n + 2\) with zeros \(\{E_0, \ldots, E_{2n+1}\} \subset \mathbb{C}\). Thus,
\[R_{2n+2}(z) = \prod_{m=0}^{2n+1} (z - E_m), \quad \{E_m\}_{m=0, \ldots, 2n+1} \subset \mathbb{C}. \quad (2.9)\]

In particular, there is a naturally associated hyperelliptic curve \(\mathcal{K}_n\) of genus \(n\) obtained from the characteristic equation for \(V_{n+1}\),
\[
\det(y I - iV_{n+1}(z, x)) = y^2 - G_{n+1}(z, x)^2 + F_n(z, x) H_n(z, x) = y^2 - R_{2n+2}(z) = 0,
\]
with \(I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\). The compactified curve by adding two points \(P_{\infty, q}\). The compactified curve is still denoted by \(\mathcal{K}_n\). A point \(P\) on the curve \(\mathcal{K}_n \setminus \{P_{\infty, q}\}\) is written as \(P = (z, y)\), where \(y^2 = R_{2n+2}(z)\).

For precise definitions of detailed properties of the curve \(\mathcal{K}_n\) we refer to Appendix A in [11].

The stationary AKNS hierarchy is obtained by enforcing the stationary zero-curvature relation
\[-V_{n+1,x} + [U, V_{n+1}] = 0, \quad (2.11)\]
which, using (2.2), (2.4), and (2.5), reduces to
\[
-V_{n+1,x} + [U, V_{n+1}] = \begin{pmatrix}
ig_{n+1,x} - ipF_n - iqH_n & -iF_{n,x} + 2xF_n + 2iqG_{n+1} \\
(H_{n,x} + 2xF_n - 2iqG_{n+1}) & -iG_{n+1,x} + ipF_n + qH_n
\end{pmatrix}
= \begin{pmatrix}
ig_{n+1,x} - ipf_n - iq\eta_n & -2f_{n+1} \\
-2\eta_{n+1} & -ig_{n+1,x} + ipf_n + iq\eta_n
\end{pmatrix} = 0. \quad (2.12)
\]

Hence the stationary AKNS hierarchy is defined by
\[
\begin{align*}
&\begin{pmatrix} h_{n+1} \\ f_{n+1} \end{pmatrix} = 0, \quad n \in \mathbb{N}_0. \\
\end{align*} \quad (2.14)
\]

Explicitly, the first few equations read
\[
\begin{align*}
n = 0: & \begin{pmatrix} -p_x + c_1(-2ip) \\ -q_x + c_1(2iq) \end{pmatrix} = 0, \\
n = 1: & \begin{pmatrix} \frac{1}{2}p_{xx} - ip^2q + c_1(-p_x) + c_2(-2ip) \\ -\frac{1}{2}q_{xx} + ipq^2 + c_1(-q_x) + c_2(2iq) \end{pmatrix} = 0, \\
\end{align*} \quad (2.15)
\]
etc.

Next we introduce a deformation parameter \(t_n \in \mathbb{C}\) in the functions \(p, q\) such that, is \(p = p(x, t_n)\), \(q = q(x, t_n)\). The time dependent zero-curvature relation then reads
\[U_{t_n} - V_{n+1,x} + [U, V_{n+1}] = 0. \quad (2.16)\]

Employing (2.1), (2.12), and (2.13), one finds
\[
U_{t_n} - V_{n+1,x} + [U, V_{n+1}] = \begin{pmatrix}
ig_{n+1,x} - ipf_n - iq\eta_n & q_{t_n} - iF_{n,x} + 2xF_n + 2iqG_{n+1} \\
p_{t_n} + iH_{n,x} - 2xF_n - 2ipG_{n+1} & -iG_{n+1,x} + ipf_n + q\eta_n
\end{pmatrix}
= \begin{pmatrix}
ig_{n+1,x} - ipf_n - iq\eta_n & q_{t_n} - 2f_{n+1} \\
p_{t_n} - 2\eta_{n+1} & -ig_{n+1,x} + ipf_n + iq\eta_n
\end{pmatrix} = 0. \quad (2.17)
\]

Hence the AKNS hierarchy is defined by
\[
\begin{align*}
&\text{AKNS}_n(p, q) = \begin{pmatrix} p_{t_n} - 2h_{n+1} \\ q_{t_n} - 2f_{n+1} \end{pmatrix} = 0, \quad n \in \mathbb{N}_0. \\
\end{align*} \quad (2.19)
\]
Explicitly, the first few equations read

\[
\begin{align*}
AKNS_0(p, q) &= \left( p_0 - p_x + c_1(-2ip) \right) = 0, \\
AKNS_1(p, q) &= \left( p_1 + \frac{1}{2} p_{xx} - i p^2 q + c_1(-p_x) + c_2(-2ip) \right) = 0,
\end{align*}
\]

etc.

We also recall a scale invariance of the AKNS hierarchy (see [11] for details). Suppose \((p, q)\) satisfies one of the AKNS equations \((2.19)\) for some \(n \in \mathbb{N}_0\),

\[
AKNS_n(p, q) = 0
\]

and consider the scale transformation

\[
(p(x, t_n), q(x, t_n)) \rightarrow (\tilde{p}(x, t_n), \tilde{q}(x, t_n)) = (A p(x, t_n), A^{-1} q(x, t_n)), \quad A \in C_1(0).
\]

Then

\[
AKNS_n[\tilde{p}, \tilde{q}] = 0.
\]

The outlined recursive approach is not confined to the hierarchy of AKNS evolution equations. Analogous considerations apply to the KdV, Toda, Boussinesq hierarchy, etc. (see [2], [9], [10], [12] and the references therein).

Next we turn to the class of algebro-geometric solutions of the AKNS hierarchy. For brevity we present the formulas in the time-dependent setting only. The corresponding stationary formulas easily follow as a special case (cf. [11]). Let \((p^{(00)}, q^{(00)})\) be a solution of the \(n\)th stationary AKNS system, that is,

\[
f_{n+1}(p^{(00)}, q^{(00)}) = \tilde{h}_{n+1}(p^{(00)}, q^{(00)}) = 0,
\]

for a given set \(\{c_j\}_{j=1}^{n+1} \subset \mathbb{C}\) of integration constants. Consider subsequently the \(r\)th time-dependent AKNS system for some fixed \(r \in \mathbb{N}_0\), with integration constants \(\{c_j\}_{j=1}^{r+1} \subset \mathbb{C}\). The corresponding quantities \(f_j, g_j, \tilde{f}_j, \tilde{g}_j, \tilde{h}_j\), etc. (that is, with \(c_1, \ldots, c_{r+1}\) replaced by \(\tilde{c}_1, \ldots, \tilde{c}_{r+1}\)), for this system will be denoted with a tilde, \(\tilde{f}_j, \tilde{g}_j, \tilde{h}_j, \tilde{V}_r, \tilde{V}_{r+1}\), etc. Thus, we are interested in the construction of solutions \((p, q)\) of

\[
AKNS_n(p, q) = \left( p_{1x} - 2h_{r+1} \right) = 0, \quad (p, q)|_{t_1 = 0, r} = (p^{(00)}, q^{(00)}).
\]

These algebro-geometric AKNS solutions are obtained by a careful analysis of two specific functions on \(\mathcal{K}_n\). First one defines the meromorphic function \(\phi\) on \(\mathcal{K}_n\) by

\[
\phi(P, x, t_r) = \frac{y(P) + G_{n+1}(x, x, t_r)}{F_n(x, x, t_r)} = \frac{-H_n(x, x, t_r)}{y(P) - G_{n+1}(x, x, t_r)},
\]

where \(P = (x, y) \in \mathcal{K}_n\).

The divisor of \(\phi(P, x, t_r)\) is given by

\[
(\phi(P, x, t_r)) = D_{P=x, y'(x, t_r)} - D_{P=x, y'(x, t_r)}.
\]

Here

\[
\hat{\mu}(x, t_r) = (\hat{\mu}_1(x, t_r), \ldots, \hat{\mu}_n(x, t_r)) \in \mathfrak{g}^*\mathcal{K}_n,
\]

and

\[
\hat{\nu}(x, t_r) = (\hat{\nu}_1(x, t_r), \ldots, \hat{\nu}_n(x, t_r)) \in \mathfrak{g}^*\mathcal{K}_n,
\]

where \(\sigma^*\mathcal{K}_n\) denotes the \(n\)th symmetric power of \(\mathcal{K}_n\) and

\[
D_{Q_0, Q}(P) = D_{Q_0} + D_{Q}, \quad D_{Q} = D_{Q_1} + \cdots + D_{Q_n},
\]
and for any $Q \in \mathcal{K}_n$,

$$Q = (Q_1, \ldots, Q_n) \in \sigma^n \mathcal{K}_n, \quad Q_0 \in \mathcal{K}_n.$$

(2.30)

$$D_Q: \mathcal{K}_n \to \mathbb{N}, \quad P \mapsto D_Q(P) = \begin{cases} 1 & \text{for } P = Q, \\ 0 & \text{for } P \in \mathcal{K}_n \setminus \{Q\}. \end{cases}$$

(2.31)

Secondly, we introduce the Baker–Akheizer vector,

$$\Psi(P, x, x_0, t_0, t_r) = \left( \frac{\psi_1(P, x, x_0, t_0, t_r)}{\psi_0(P, x, x_0, t_0, t_r)} \right),$$

(2.32)

$$\psi_1(P, x, x_0, t_0, t_r) = \exp \left( -i \int_{t_0}^{t_r} dz' (z' + q(z', t_r) \phi(P, z', t_r)) + i \int_{t_0}^{t_r} ds (\bar{F}_n(z, x_0, s) \phi(P, x_0, s) - \bar{G}_{n+1}(z, x_0, s)) \right),$$

$$\psi_0(P, x, x_0, t_0, t_r) = \phi(P, x, t_r) \psi_1(P, x, x_0, t_0, t_r), \quad P \in \mathcal{K}_n \setminus \{P_{\infty} \}, \quad (x, t_r) \in \mathbb{C}^2.$$

The functions $\phi$ and $\psi$ satisfy the fundamental properties.

**Theorem 2.1** (see [10], [11]). Let $P = (z, y) \in \mathcal{K}_n \setminus \{P_{\infty} \}$ and $(z, x, x_0, t_0, t_r) \in \mathbb{C}^5$. Then $\phi(P, x, t_r)$ satisfies

$$\phi_2(P, x, t_r) + q(z, t_r) \phi(P, x, t_r)^2 - 2iz\phi(P, x, t_r) = p(x, t_r),$$

(2.33)

and $\Psi(\cdot, x_0, t_0, t_r)$ fulfills

$$\Psi_2(P, x, x_0, t_0, t_r) = U(z, x, t_r) \Psi(P, x, x_0, t_0, t_r),$$

(2.34)

$$ig(P) \Psi(P, x, x_0, t_0, t_r) = V_{n+1}(z, x, t_r) \Psi(P, x, x_0, t_0, t_r),$$

(2.35)

$$\Psi_{t_r}(P, x, x_0, t_0, t_r) = \bar{V}_{t_r+1}(z, x, t_r) \Psi(P, x, x_0, t_0, t_r).$$

(2.36)

In addition, as long as the zeros of $F_{n+1}(z, t_r)$ are all simple for $(z, t_r) \in \Omega, \Omega \subseteq \mathbb{R}^2$ open and connected, $\Psi(\cdot, x_0, t_0, t_r)$, $(z, t_r), (x_0, t_0, t_r) \in \Omega$, is meromorphic on $\mathcal{K}_n \setminus \{P_{\infty} \}$.

Further properties of $\phi$ and $\Psi$ can be found in [11], Lemma 4.1.

In order to express the basic quantities in terms of Riemann's theta function associated with $\mathcal{K}_n$, we need to introduce differentials and some more notation in connection with the hyperelliptic curve $\mathcal{K}_n$. In the following we assume $\mathcal{K}_n$ to be nonsingular, that is,

$$E_m \neq E_{m'}, \quad m, m' = 0, \ldots, 2n + 1, \quad m \neq m'.$$

(2.37)

Given a canonical homology basis $\{a_j, b_j\}_{j=1, \ldots, n}$ for $\mathcal{K}_n$ with intersection matrix $a_j \circ b_k = \delta_{j,k}$, one denotes by $\omega_j, j = 1, \ldots, n$ a normalized basis of the space of holomorphic differentials on $\mathcal{K}_n$,

$$\int_{a_k} \omega_j = \delta_{j,k}, \quad j, k = 1, \ldots, n.$$

(2.38)

In addition, one considers a canonical dissection of $\mathcal{K}_n$ along its cycles yielding the simply connected interior $\mathcal{K}_n$ of the fundamental polygon

$$\partial \mathcal{K}_n = a_1 a_2^{-1} \cdots a_n^{-1} b_n^{-1}.$$

(2.39)

Next, we choose, without loss of generality, the base point $P_0 = (E_0, 0) \in \mathcal{K}_n$ and denote by $A_{P_0}$, $\Omega_{P_0}$ the Abel maps

$$A_{P_0}: \mathcal{K}_n \to J(\mathcal{K}_n), \quad P \mapsto A_{P_0}(P) = (A_{P_0,1}(P), \ldots, A_{P_0,n}(P))$$

$$= \left( \int_{P_0}^{P} \omega_1, \ldots, \int_{P_0}^{P} \omega_n \right) \mod L_n,$$

(2.40)
and
\[ \alpha_{P_0} : \text{Div}(K_n) \to J(K_n), \quad D \mapsto \alpha_{P_0}(D) = \sum_{P \in K_n} D(P) \tilde{\alpha}_{P_0}(P), \]
where
\[ L_n = \{ z \in \mathbb{C}^n \mid z = \mathbf{N} + \tau \mathbf{M}, \mathbf{N}, \mathbf{M} \in \mathbb{Z}^n \} \]
denotes the period lattice, and
\[ J(K_n) = \mathbb{C}^n / L_n \]
the Jacobi variety. In addition we introduce
\[ \tilde{\alpha}_{P_0} : \tilde{K}_n \to \mathbb{C}^n, \quad P \mapsto \tilde{\alpha}_{P_0}(P) = (\tilde{\alpha}_{P_0,1}(P), \ldots, \tilde{\alpha}_{P_0,n}(P)) \]
\[ = \left( \int_{P_0}^{P} \omega_1, \ldots, \int_{P_0}^{P} \omega_n \right), \] (2.44)
\[ \tilde{\alpha}_{P_0} : \text{Div}(K_n) \to \mathbb{C}^n, \quad D \mapsto \tilde{\alpha}_{P_0}(D) = \sum_{P \in K_n} D(P) \tilde{\alpha}_{P_0}(P), \] (2.45)
and \( \Xi_{P_0} = (\Xi_{P_0,1}, \ldots, \Xi_{P_0,n}) \), the vector of Riemann constants, by
\[ \Xi_{P_0} = \tilde{\Xi}_{P_0} \bmod L_n, \]
\[ \Xi_{P_0,j} = \frac{1}{2} \left( 1 + \sum_{j \neq j} \int_{b_j} \omega_j \right) - \sum_{j \neq j} \int_{b_j} \omega_j(P) \tilde{\alpha}_{P_0,j}(P), \quad j = 1, \ldots, n. \] (2.46)

Next, consider the normal differential of the third kind \( \omega_{P_{0n},P_{-n}}^{(3)} \) with simple poles at \( P_{0n} \) and \( P_{-n} \), corresponding residues +1 and -1, vanishing \( a \)-periods, being holomorphic otherwise on \( K_n \). Hence one obtains
\[ \omega_{P_{0n},P_{-n}}^{(3)} = \frac{\prod_{j=1}^{n} (\bar{\eta} - \lambda_j) d\bar{\eta}}{y}, \quad \omega_{P_{-0n},P_{0n}}^{(3)} = -\omega_{P_{0n},P_{-n}}^{(3)}, \] (2.47)
\[ \int_{b_j} \omega_{P_{0n},P_{-n}}^{(3)} = 0, \quad j = 1, \ldots, n, \] (2.48)
\[ U_{(3)}^{(3)} = (U_{(3)}^{(3)}, \ldots, U_{n}^{(3)}), \]
\[ U_{(3)}^{(3)} = \frac{1}{2\pi i} \int_{b_j} \omega_{P_{0n},P_{-n}}^{(3)} \tilde{\alpha}_{P_{-0n},P_{0n}}(P_{0n}) = 2\tilde{\alpha}_{P_{-0n},P_{0n}}(P_{0n}), \quad j = 1, \ldots, n, \] (2.49)
\[ \int_{b_0}^{P} \omega_{P_{0n},P_{-n}}^{(3)} \equiv \pm (\ln(\zeta) - \ln(\omega_0) + O(1)), \quad P = (\zeta^{-1}, y) \text{ near } P_{0n}, \] (2.50)
where the numbers \( \{ \lambda_j \}_{j=1, \ldots, n} \) are determined by the normalization (2.48). The Abelian differentials of the second kind \( \omega_{P_{0n},0}^{(2)} \) are chosen such that
\[ \omega_{P_{0n},0}^{(2)} \equiv \zeta^{-0} (\zeta^{-2} + O(1)) d\zeta \text{ near } P_{0n}, \] (2.51)
\[ \int_{b_j} \omega_{P_{0n},0}^{(2)} = 0, \quad j = 1, \ldots, n, \] (2.52)
\[ U_{0}^{(2)} = (U_{0,1}^{(2)}, \ldots, U_{0,n}^{(2)}), \quad U_{0}^{(2)} = \frac{1}{2\pi i} \int_{b_j} \omega_{0}^{(2)} \quad \Omega_{0}^{(2)} = \omega_{P_{0n},0}^{(2)} - \omega_{P_{-0n},0}^{(2)}, \] (2.53)
\[ \int_{P_{0}}^{P} \Omega_{0}^{(2)} \equiv \mp (\zeta^{-1} + e_{0,0} + e_{0,1} \zeta + O(\zeta^2)), \quad P = (\zeta^{-1}, y) \text{ near } P_{0n}. \] (2.54)
In addition we define Abelian differentials of the second kind $\omega^{(2)}_{\mathcal{P}_{m+n,r}}$ by
\begin{equation}
\omega^{(2)}_{\mathcal{P}_{m+n,r}} = (\zeta^{-2-r} + O(1)) d\zeta \text{ near } P_{m+n}, \; r \in \mathbb{N},
\end{equation}
\begin{equation}
\int_{a_j} \omega^{(2)}_{\mathcal{P}_{m+n,r}} = 0, \quad j = 1, \ldots, n,
\end{equation}
\begin{equation}
\tilde{\zeta}_r = (\tilde{\zeta}^{(2)}_{r,1}, \ldots, \tilde{\zeta}^{(2)}_{r,n}), \quad \tilde{\zeta}^{(2)}_{r,j} = \frac{1}{2\pi i} \int_{a_j} \tilde{\Omega}^{(2)}_r,
\end{equation}
\begin{equation}
\tilde{\Omega}^{(2)}_r = \sum_{q=0}^{r} (q+1) \tilde{\epsilon}_{r,q} \omega^{(2)}_{\mathcal{P}_{m+n,q}} + O(\zeta), \quad P = (\zeta^{-1}, y) \text{ near } P_{m+n},
\end{equation}
with $\{\tilde{\epsilon}_{r}\}_{r=1,\ldots,n} \subset \mathbb{C}$, $\tilde{\epsilon}_0 = 1$ denoting integration constants.

Finally, we abbreviate
\begin{equation}
\tilde{z}(P; Q) = \tilde{A}_{P}(P) - \tilde{A}_{Q}(Q),
\end{equation}
\begin{equation}
\tilde{z}(P; Q) = \tilde{z}(P_{m+n}, Q) = \tilde{z}(Q_{1}, \ldots, Q_{n}).
\end{equation}

Next, assume that $(p, q)$ satisfies the $n$th time-dependent AKNS equation with initial data $(p^{(0)}, q^{(0)})$ being solutions of the $n$th stationary AKNS equation at $t = t_{0,r}$, that is,
\begin{equation}
(p(x, t_{0,r}), q(x, t_{0,r})) = (p^{(0)}(x), q^{(0)}(x)), \quad x \in \mathbb{C}.
\end{equation}

The principal aim is to derive explicit formulas for the solution $(p, q)$ as well as the function $\varphi$ and the Baker–Akhiezer function $\Psi$ in terms of the Riemann theta function
\begin{equation}
\theta(z) = \sum_{m \in \mathbb{Z}^n} \exp(2\pi i (m, z) + \pi i (m, \tau m)), \quad z \in \mathbb{C}^n,
\end{equation}
\begin{equation}
\theta(z) = \sum_{m \in \mathbb{Z}^n} \exp(2\pi i (m, z) + \pi i (m, \tau m)), \quad z \in \mathbb{C}^n.
\end{equation}

This is the content of the next theorem.

**Theorem 2.2** (see [10], [11]). Let $P \in \mathcal{K}_n \setminus \{P_{m+n}\}$, $(x, x_{0}, t_{0}, t_{r}, r) \in \mathbb{C}^4$, assume $K_n$ to be nonsingular, and suppose $D_{\mathcal{P}_{m+n,r}}$ and $D_{\mathcal{P}_{m+n,r}}$ to be nonspecial, that is, their index of speciality vanishes, $i(D_{\mathcal{P}_{m+n,r}}) = i(D_{\mathcal{P}_{m+n,r}}) = 0$. Moreover, suppose that $(p, q)$ satisfies the AKNS system $(p, q) = (p^{(0)}, q^{(0)})$, a solution of the $n$th stationary AKNS system. Let $\varphi$ and $\Psi$ be defined by (2.26) and (2.32), respectively. Then
\begin{equation}
\varphi(P, x, t_r) = \frac{2i}{q(x_0, t_{0,r})} \int_{P_{m+n, r}} \omega^{(2)}_{\mathcal{P}_{m+n,r}} - 2i(x - x_0)\tilde{\epsilon}_{r,0} - 2i(t_r - t_{0,r})\tilde{\epsilon}_{r,0}
\end{equation}
\begin{equation}
\times \exp \left( \int_{P_{m+n, r}} \tilde{\zeta}_r^{(2)} \right),
\end{equation}
\begin{equation}
\psi_1(P, x, x_{0}, t_{0}, t_{r}, r) = \frac{\theta(z_{-}(\tilde{\mu}(x_0, t_{0,r})) \theta(z_{+}(P, \tilde{\mu}(x, t_r))))}{\theta(z_{+}(\tilde{\mu}(x_0, t_{0,r})) \theta(z_{-}(P, \tilde{\mu}(x, t_r)))) \times
\end{equation}
\begin{equation}
\times \exp \left( \int_{P_{m+n, r}} \tilde{\zeta}_r^{(2)} \right),
\end{equation}
\begin{equation}
\psi_2(P, x, x_{0}, t_{0}, t_{r}, r) = \frac{2i}{q(x_0, t_{0,r})} \int_{P_{m+n, r}} \omega^{(2)}_{\mathcal{P}_{m+n,r}} + i(x - x_0)(-\tilde{\epsilon}_{r,0} + \int_{P_{m+n, r}} \tilde{\zeta}_r^{(2)}.),
\end{equation}
\begin{equation}
\times \exp \left( \int_{P_{m+n, r}} \omega^{(2)}_{\mathcal{P}_{m+n,r}} + i(x - x_0)(-\tilde{\epsilon}_{r,0} + \int_{P_{m+n, r}} \tilde{\zeta}_r^{(2)}).ight.
\end{equation}
Furthermore, one derives

$$p(x; t_r) = p(x_0; t_0, r) \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))} \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))} \times
\exp(-2i(x - x_0)e_0 + 2i(t_r - t_0, r)e_0 - 2i(t_r - t_0, r)e_0 - 2i(t_r - t_0, r)e_0),$$

$$q(x; t_r) = q(x_0; t_0, r) \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))} \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))} \times
\exp(2i(x - x_0)e_0 + 2i(t_r - t_0, r)e_0) e_0),$$

$$p(x_0; t_0, r)q(x_0; t_0, r) = \frac{4}{\omega \theta(x_0; \mu(x_0, t_0, r))} \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))} \frac{\theta(x_0; \mu(x_0, t_0, r))}{\theta(x_0; \mu(x_0, t_0, r))},$$

and

$$\Omega_{\mu_1}(x; t_r) = \alpha \theta(x_0; \mu(x_0, t_0, r)) - i(x - x_0) / \theta(x_0; \mu(x_0, t_0, r)),$$

$$\Omega_{\mu_2}(x; t_r) = \alpha \theta(x_0; \mu(x_0, t_0, r)) - i(x - x_0) / \theta(x_0; \mu(x_0, t_0, r)).$$

Algebro-geometric solutions of the AKNS equations (i.e., the case \( r = 1, n \in \mathbb{N} \)) have previously been derived by a variety of authors, see, for instance, [1], [6], [7], [16], [17], [22], [26], [28], [29] and the literature cited therein. The principal contribution of [11] to this circle of ideas is an effortless treatment of algebro-geometric solutions of the entire AKNS hierarchy (i.e., for \( r, n \in \mathbb{N} \)) using the elementary polynomial recursion formalism outlined in the first part of this section.

3. The classical Boussinesq hierarchy

In this section we follow the zero-curvature formalism introduced by Geng and Wu [8] for the cBq hierarchy and adapt it to the recursion formalism outlined in Section 2. Fix \( \alpha \in \mathbb{C}, \beta \in \mathbb{C}, \) and define the matrix

$${\mathcal{U}}(z;x) = \begin{pmatrix} -iz - \alpha(x) & u(x) + \beta v(x) \\ - \alpha(x) & iz + \alpha(x) \end{pmatrix}. \tag{3.1}$$

Define recursively \( \{\mathcal{J}_j(x)\}_{j \in \mathbb{N}_0}, \{\mathcal{G}_j(x)\}_{j \in \mathbb{N}_0}, \) and \( \{\mathcal{H}_j(x)\}_{j \in \mathbb{N}_0}, \) by

$$\mathcal{J}_0(x) = -i(u(x) + \beta v(x)), \quad \mathcal{G}_0(x) = 1, \quad \mathcal{H}_0(x) = -i,$$

$$\mathcal{J}_{j+1}(x) = \frac{i}{2} \mathcal{J}_j(x) + i\alpha(x) \mathcal{J}_j(x) - i(u(x) + \beta v(x)) \mathcal{G}_{j+1}(x),$$

$$\mathcal{G}_{j+1}(x) = (u(x) + \beta v(x)) \mathcal{H}_{j+1}(x) - \mathcal{J}_j(x),$$

$$\mathcal{H}_{j+1}(x) = -\frac{i}{2} \mathcal{H}_j(x) + i\alpha(x) \mathcal{H}_j(x) - \mathcal{G}_{j+1}(x), \quad j \in \mathbb{N}_0. \tag{3.2d}$$

Explicitly, the first few elements read

$$\mathcal{J}_1 = \frac{1}{2} (u + \beta v), \quad \mathcal{G}_1 = -2i(u + \beta v), \quad \mathcal{H}_1 = \alpha v - i\alpha,$$

$$\mathcal{G}_1 = \alpha v - i\alpha,$$

$$\mathcal{H}_1 = \alpha v - i\alpha,$$

$$\varepsilon = -\alpha.$$ 

\footnote{The constants \( \alpha \) and \( \beta \) remain fixed in the following and will not be emphasized in the notation.}
where \( \{c_j\}_{j \in \mathbb{N}} \subset \mathbb{C} \) are integration constants.

Next, define
\[
\nabla_{n+1}(z, \bar{z}) = i \begin{pmatrix}
-\overline{G}_{n+1}(z, x) & \overline{F}_{n}(z, x) \\
-\overline{H}_{n}(z, x) & \overline{G}_{n+1}(z, x)
\end{pmatrix}
\]
(3.4)
where \( \overline{F}_{n}(z, x), \overline{G}_{n+1}(z, x), \) and \( \overline{H}_{n}(z, x) \) are polynomials in \( z \in \mathbb{C} \).

\[
\overline{F}_{n}(z, x) = \sum_{\ell=0}^{n} f_{n-\ell}(x)z^{\ell} = -i(u(x) + \beta v_{\bar{z}}(x)) \prod_{j=1}^{n}(z - \overline{\mu}_{j}(x)),
\]
(3.5)
\[
\overline{G}_{n+1}(z, x) = \sum_{\ell=0}^{n+1} g_{n+1-\ell}(x)z^{\ell},
\]
\[
\overline{H}_{n}(z, x) = \sum_{\ell=0}^{n} h_{n-\ell}(x)z^{\ell} = -i \prod_{j=1}^{n}(z - \overline{\nu}_{j}(x)).
\]

Using the recursion (3.2) one verifies
\[
\overline{F}_{n,x} = -2(i\alpha + \alpha \overline{F}_{n} + 2(u + \beta v_{\bar{z}})\overline{G}_{n+1},
\]
\[
\overline{G}_{n+1,x} = (u + \beta v_{\bar{z}})\overline{H}_{n} - \overline{F}_{n},
\]
\[
\overline{H}_{n,x} = 2(i\alpha + \alpha \overline{H}_{n} - 2\overline{G}_{n+1},
\]
(3.6)

implying
\[
(\overline{G}_{n+1} - \overline{F}_{n}\overline{H}_{n})_{x} = 0
\]
(3.7)
and hence
\[
\overline{G}_{n+1}(z, x)^{2} - \overline{F}_{n}(z, x)\overline{H}_{n}(z, x) = R_{2n+2}(z),
\]
(3.8)
where \( R_{2n+2}(z) \) is a monic polynomial of degree \( 2n + 2 \) with zeros \( \{\overline{E}_{0}, \ldots, \overline{E}_{2n+1}\} \subset \mathbb{C} \). Thus,
\[
R_{2n+2}(z) = \prod_{m=0}^{2n+1} (z - \overline{E}_{m}), \quad \{\overline{E}_{m}\}_{m=0, \ldots, 2n+1} \subset \mathbb{C}.
\]
(3.9)

Again the corresponding hyperelliptic curve \( \mathcal{K}_{n} \) of genus \( n \) is naturally obtained from the characteristic equation for \( V_{n+1} \),
\[
\det(yI - iV_{n+1}(z, x)) = y^{2} - \overline{G}_{n+1}(z, x)^{2} + \overline{F}_{n}(z, x)\overline{H}_{n}(z, x)
\]
\[
= y^{2} - R_{2n+2}(z) = 0.
\]
(3.10)

The corresponding zero-curvature relation then reads, employing (3.4) and (3.5),
\[
-\nabla_{n+1,x} + [\overline{U}, \nabla_{n+1}]
\]
\[
= i \begin{pmatrix}
\overline{G}_{n+1,x} + f_{n} - (u + \beta v_{\bar{z}})h_{n} & -f_{n,\bar{z}} - 2(i\alpha + \alpha f_{n}) + 2(u + \beta v_{\bar{z}})g_{n+1}\n
-f_{n,\bar{z}} - 2(i\alpha + \alpha f_{n}) + 2(u + \beta v_{\bar{z}})g_{n+1} & -\overline{G}_{n+1,x} + f_{n} - (u + \beta v_{\bar{z}})h_{n}
\end{pmatrix} = 0.
\]
(3.11)

Using the recursion (3.2) to compute \( f_{j}, g_{j}, \) and \( h_{j} \) for \( j = 0, \ldots, n \), (3.11) equals
\[
-\nabla_{n+1,x} + [\overline{U}, \nabla_{n+1}]
\]
\[
= i \begin{pmatrix}
g_{n+1,x} + f_{n} - (u + \beta v_{\bar{z}})h_{n} & -f_{n,\bar{z}} - 2(i\alpha + \alpha f_{n}) + 2(u + \beta v_{\bar{z}})g_{n+1}\n
-f_{n,\bar{z}} - 2(i\alpha + \alpha f_{n}) + 2(u + \beta v_{\bar{z}})g_{n+1} & -g_{n+1,x} + f_{n} - (u + \beta v_{\bar{z}})h_{n}
\end{pmatrix} = 0.
\]
(3.12)

Next, let
\[
g_{n+1} = -\frac{1}{2}h_{n,\bar{z}} - i\alpha \overline{h}_{n}
\]
(3.13)
(consistent with \( h_{n+1} = 0 \) in (3.2d)). Inserting (3.13) into (3.12), we find that the stationary cbSq hierarchy is given by
\[
\begin{pmatrix}
f_{n,x} + 2(i\alpha + \alpha f_{n}) + (u + \beta v_{\bar{z}})(h_{n,\bar{z}} - 2i\alpha h_{n})

-\frac{1}{2}h_{n,\bar{z}} + i\alpha(h_{n,\bar{z}}) + f_{n} - (u + \beta v_{\bar{z}})h_{n}
\end{pmatrix} = 0, \quad n \in \mathbb{N}_{0}.
\]
(3.14)
Remark 3.1. Observe that due to (3.13), the nth stationary cBsq system will contain only integration constants $c_1, \ldots, c_n$ for $n \in \mathbb{N}$ coming from integrating (3.2c). Since we have $\bar{y}_{n+1,x} + \bar{f}_n - (u + \beta v_x)\bar{h}_n = 0$ from (3.12), our definition (3.13) is consistent with the definition of $\bar{y}_{n+1}$ given by the recursion (3.2c). However, no new integration constant is introduced.

The first few equations (after some simplifications) read
\begin{align}
    n = 0 : & \quad \left( \begin{array}{c}
u_x \\ v_x \\ \end{array} \right) = 0, \\
    n = 1 : & \quad \left( \begin{array}{c}(u + \beta v_x)x + 4\alpha(u + \beta v_x)v_x - \alpha u_x + \beta u_x \\ u_x + \beta u_x + 2\alpha^2 v_x^2 - 2\alpha v_x \end{array} \right) = 0,
\end{align}

(3.15)
on etc.

In the special homogeneous case, the latter set of equations, the stationary classical Boussinesq system, can be rewritten in the more familiar form
\begin{align}
    u + \beta v_x + 2\alpha^2 v_x = 0, \quad (2\alpha \beta - \beta^2)v_x + (\alpha - \beta)u_x + 4\alpha^2 u v_x = 0.
\end{align}

(3.16)

Using the first equation in (3.16), the second can also be rewritten as $u v_x = 12\alpha^2 (v_x^2) = 0$.

To discuss the time-dependent hierarchy of classical Boussinesq systems we follow the AKNS case and introduce a deformation parameter $t_n \in \mathbb{C}$ in the functions $u$ and $v$, that is, $u = u(x, t_n), \ v = v(x, t_n)$. The time-dependent zero-curvature relation then reads
\begin{align}
    \bar{U}_{t_n} - \bar{V}_{n+1,x} + [\bar{U}, \bar{V}_{n+1}] = 0,
\end{align}

(3.17)

implying
\begin{align}
    0 = \bar{U}_{t_n} - \bar{V}_{n+1,x} + [\bar{U}, \bar{V}_{n+1}]
    = \left( \begin{array}{c}
    -\alpha u_x - \beta u_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} \\
    \alpha v_x - \beta v_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} \\
    \end{array} \right).
\end{align}

(3.18)

Using now the recursion (3.2) to compute $\bar{f}_j, \bar{g}_j$, and $\bar{h}_j$ for $j = 0, \ldots, n$, (3.18) reduces to
\begin{align}
    \bar{U}_{t_n} - \bar{V}_{n+1,x} + [\bar{U}, \bar{V}_{n+1}]
    = \left( \begin{array}{c}
    -\alpha u_x - \beta u_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} \\
    \alpha v_x - \beta v_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} \\
    \end{array} \right) = 0,
\end{align}

(3.19)

or equivalently,
\begin{align}
    \alpha u_x - \beta u_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} = 0, \\
    (u + \beta v_x)_x - \bar{f}_{n+1,x} - 2i(u + \beta v_x)\bar{g}_{n+1} = 0,
\end{align}

(3.20a, 3.20b)

\begin{align}
    \bar{h}_{n,x} - 2\alpha v_x + 2\bar{g}_{n+1} = 0.
\end{align}

(3.20c)

Using $\bar{h}_{n,x} - 2\alpha v_x + 2\bar{g}_{n+1} = 0$ in order to eliminate $\bar{g}_{n+1}$ in (3.20a) and (3.20b), then yields the following expressions for the time-dependent classical Boussinesq hierarchy,
\begin{align}
    \alpha u_x - \beta u_x + 2v_x + 2(u + \beta v_x) \bar{h}_n - (u + \beta v_x)_x - 2i(u + \beta v_x)_x + 2i(u + \beta v_x)\bar{f}_{n+1} = 0,
\end{align}

(3.21)

For brevity, equations (3.21) will be denoted by
\begin{align}
    cBSq_n((u, v) = 0, \ n \in \mathbb{N}).
\end{align}

(3.22)

Remark 3.2. Observe that $\bar{g}_{n+1}$ defined by (3.20c) does not satisfy (3.2c), but rather (3.20a). This is in contrast to the stationary case as well as the corresponding definitions for the AKNS hierarchy.

As in the stationary case, the nth cBsq system contains $n$ integration constants $c_1, \ldots, c_n$ for $n \in \mathbb{N}$. 
Explicitly, the first few equations read
\begin{align}
\text{cBsq}_0(u, v) &= \left( \frac{\alpha u_x - \alpha v_z}{\alpha v_x - \alpha v_z} \right) = 0, \tag{3.23} \\
\text{cBsq}_1(u, v) &= \left( \frac{\alpha u_{zz} - \frac{i}{2} (\beta - \alpha) u_{zz} + \frac{i}{2} (\beta - \alpha) u_{xx} - 2i \alpha^2 u v_x + c_1 (-\alpha u_z)}{\alpha v_{xx} - \frac{i}{2} (\beta - \alpha) u_{xx} + 2i \alpha^2 v v_x + c_1 (-\alpha v_z)} \right) = 0,
\end{align}
e tc.

In the homogeneous case \( \text{cBsq}_1(u, v) = 0 \) can be rewritten as
\begin{align}
\alpha u_{zz} &= \frac{i}{2} (\beta - \alpha) u_{xx} + \frac{i}{2} (\alpha - \beta) u_{zz} + 2i \alpha^2 (u v)_x, \\
\alpha v_{xx} &= \frac{i}{2} (\beta - \alpha) u_{xx} + 2i \alpha^2 v v_x + \frac{i}{2} u_z.
\end{align}

Finally, specializing to \( \alpha = \beta \) one obtains the classical Boussinesq system
\begin{align}
u_t &= \frac{i}{2} \alpha u_{xx} + 2i \alpha (u v)_x, \quad \alpha v_t = 2i \alpha^2 v v_x + \frac{i}{2} u_z.
\end{align}

In the next section we provide a new proof of the fact that the AKNS and the cBsq hierarchies are gauge equivalent by exhibiting an explicit gauge transformation between them. In the last section this will be used to derive algebro-geometric solutions of the cBsq hierarchy.

4. THE GAUGE EQUIVALENCE OF THE CBSQ AND AKNS HIERARCHIES

We start by briefly recalling the effect of gauge transformations on zero-curvature equations. Starting with the time-dependent equations
\begin{align}
\Psi_x = U \Psi, \quad \Psi_t = V \Psi, \quad \Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix},
\end{align}
whose compatibility relation \( \Psi_{xt} = \Psi_{tx} \) yields the zero-curvature equation
\begin{align}
U_t - V_x + [U, V] = 0,
\end{align}
we introduce the gauge transformation
\begin{align}
\overline{\Psi} = S \Psi, \quad S \text{ invertible}.
\end{align}
Then one derives,
\begin{align}
\overline{\Psi}_x = \overline{U} \overline{\Psi}, \quad \overline{\Psi}_t = \overline{V} \overline{\Psi},
\end{align}
with
\begin{align}
\overline{U} = S_x S^{-1} + S U S^{-1}, \quad \overline{V} = S_t S^{-1} + S V S^{-1}
\end{align}
and hence
\begin{align}
\overline{U}_t - \overline{V}_x + [\overline{U}, \overline{V}] = 0.
\end{align}
The corresponding stationary formalism starts from
\begin{align}
\Psi_x = U \Psi, \quad iy \Psi = V \Psi, \quad y \in \mathbb{C}
\end{align}
and
\begin{align}
- V_x + [U, V] = 0.
\end{align}
The gauge transformation (4.3) then effects
\begin{align}
\overline{\Psi}_x = \overline{U} \overline{\Psi}, \quad iy \overline{\Psi} = \overline{V} \overline{\Psi},
\end{align}
with
\begin{align}
\overline{U} = S_x S^{-1} + S U S^{-1}, \quad \overline{V} = S V S^{-1}
\end{align}
and hence
\begin{align}
- \overline{V}_x + [\overline{U}, \overline{V}] = 0.
\end{align}
Introducing the particular choice
\[
S = \begin{pmatrix} (-p)^{1/2} & 0 \\ 0 & 1/(-p)^{1/2} \end{pmatrix}, \quad p \text{ meromorphic on } \mathbb{C}
\] (4.12)
and applying it to (4.7)–(4.11) in the case of the stationary AKNS hierarchy, identifying \((U, V)\) and \((U, \overline{V}_{n+1})\), then yields the following result.

**Theorem 4.1.** The stationary AKNS and cBsq hierarchies are gauge equivalent in the sense that
\[
\begin{align*}
\overline{U} &= S_t S^{-1} + S U S^{-1}, & \overline{V}_{n+1} &= S V_{n+1} S^{-1},
\end{align*}
\] (4.13)
with \((U, V_{n+1})\) and \((\overline{U}, \overline{V}_{n+1})\) given by (2.1), (2.4) and (3.1), (3.4), respectively, and \(S\) defined by (4.12) (with \(p = p(x)\)). In particular, the pair \((u, v)\) given by
\[
\begin{align*}
u(x) &= -p(x)q(x) + \frac{\beta}{2\alpha} \left( \frac{p(x)}{p(x)'} \right) , & v(x) &= -\frac{1}{2\alpha} \frac{p(x)}{p(x)},
\end{align*}
\] (4.14)
satisfies the \(n\)th stationary cBsq system if and only if the pair \((p, q)\), given by
\[
\begin{align*}
 p(x) &= \exp \left( -2\alpha \int x' v(x') \right), & q(x) &= -(u(x) + \beta v_2(x)) \exp \left( 2\alpha \int x' v(x') \right),
\end{align*}
\] (4.15)
satisfies the \(n\)th stationary AKNS system with identical sets of integration constants \(c_j \in \mathbb{C}, j = 1, \ldots, n\) for \(n \in \mathbb{N}\).

**Proof.** \(\overline{U} = S_t S^{-1} + S U S^{-1}\) is easily seen to be equivalent to (4.14). Similarly, \(\overline{V}_{n+1} = S V_{n+1} S^{-1}\) is equivalent to
\[
\overline{P}_n = -p F_n, & \overline{G}_{n+1} = G_{n+1}, & H_n = -\frac{1}{p} H_n.
\] (4.16)

Next suppose that \((p, q)\) solves the \(n\)th stationary AKNS system, that is, equations (2.6) hold. Define \(\overline{F}_n, \overline{G}_{n+1}\), and \(\overline{H}_n\) by (4.16) and \((u, v)\) by (4.14). Then clearly (3.6) is satisfied, proving that \((u, v)\) satisfies the \(n\)th stationary cBsq system.

Conversely, starting with \((u, v)\) solving the \(n\)th stationary cBsq system (3.6), we can define \((p, q)\) and \(F_n, G_{n+1}\), and \(H_n\) using (4.15) and (4.16), respectively. One then easily verifies that (2.6) holds, and thus \((p, q)\) solves the \(n\)th stationary AKNS system. \(\square\)

We note that the ambiguity inherent to (4.15), due to an arbitrary integration constant, corresponds to the scale invariance of the AKNS hierarchy as discussed in (2.21)–(2.23).

The time-dependent analog of Theorem 4.1 then reads as follows.

**Theorem 4.2.** The time-dependent AKNS and cBsq hierarchies are gauge equivalent in the sense that
\[
\begin{align*}
\overline{U} &= S_t S^{-1} + S U S^{-1}, & \overline{V}_{n+1} &= S_t S^{-1} + S V_{n+1} S^{-1},
\end{align*}
\] (4.17)
with \((U, V_{n+1})\) and \((\overline{U}, \overline{V}_{n+1})\) given by (2.1), (2.4) and (3.1) and (3.4), respectively, and \(S\) defined by (4.12) (with \(p = p(x, t_n)\)). In particular, the pair \((u, v)\) given by
\[
\begin{align*}
u(x, t_n) &= -p(x, t_n)q(x, t_n) + \frac{\beta}{2\alpha} \left( \frac{p(x, t_n)}{p(x, t_n)'} \right) , & v(x, t_n) &= -\frac{1}{2\alpha} \frac{p(x, t_n)}{p(x, t_n)},
\end{align*}
\] (4.18)
satisfies the \(n\)th cBsq system \(\text{cBsq}_n(u, v) = 0\) if and only if the pair \((p, q)\) given by
\[
\begin{align*}
 p(x, t_n) &= \exp \left( -2\alpha \int x' v(x', t_n) \right), & q(x, t_n) &= -(u(x, t_n) + \beta v_2(x, t_n)) \exp \left( 2\alpha \int x' v(x', t_n) \right),
\end{align*}
\] (4.19)
satisfies the nth AKNS system \( \text{AKNS}_n(p, q) = 0 \) with identical sets of integration constants \( c_j \in \mathbb{C}, j = 1, \ldots, n \) for \( n \in \mathbb{N} \).

**Proof.** \( \bar{U} = S_n S^{-1} + S V_n S^{-1} \) is equivalent to (4.17) as noted in the proof of Theorem 4.1. By a direct calculation, \( v_{n+1} = S_n S^{-1} + S V_n S^{-1} \) is equivalent to

\[
F_n = -pF_n, \quad G_{n+1} = G_n + \frac{i}{2} \frac{p_n}{p}, \quad H_n = -\frac{1}{p} H_n.
\]

Next assume that \((p, q)\) solves the nth AKNS system, that is, equations (2.17) hold. Define \( \bar{F}_n, \quad \bar{G}_{n+1}, \) and \( \bar{H}_n \) by (4.20) and \((u, v)\) by (4.18). Then clearly (3.11) is satisfied, proving that \((u, v)\) satisfies the nth cBsq system.

Conversely, starting with \((u, v)\) solving the nth cBsq system (3.11), we can define \((p, q)\) and \( F_n, \quad G_{n+1}, \) and \( H_n \) using (4.19) and (4.20), respectively. Again one verifies that (2.17) holds, and thus \((p, q)\) solves the nth AKNS system. \( \square \)

The equivalence of the cBsq and AKNS hierarchies, on the basis of the transformation (4.17) has first been noted by Jantzen and Miolek [18] and later by Matveev and Yavor [27]. It has been further discussed and linked to Hirota’s bilinear formalism by Sachs [30]. Our method of proof of Theorems 4.1 and 4.2, based on the polynomial recursion formalism developed in Section 3, to the best of our knowledge, is new.

5. **Algebro-geometric solutions of the classical Boussinesq hierarchy**

Finally we derive the theta function representation of algebro-geometric cBsq solutions utilizing the gauge equivalence of the cBsq and AKNS hierarchies.

Let \((u^{(0)}, v^{(0)})\) be a stationary solution of the nth classical Boussinesq system, that is,

\[
\bar{f}_{n,x} + 2\alpha \bar{f}_n + (u + \beta \bar{v}_x) (\bar{h}_{n,x} - 2 \alpha \bar{h}_n) = 0,
\]

\[
\bar{f}_{n,y} - (u + \beta \bar{v}_y) \bar{h}_n - \frac{1}{2} \bar{h}_{n,xx} + \alpha (\bar{v}_n)_x = 0,
\]

for a given set of integration constants \( \{c_j\}_{j=1,\ldots,n} \subset \mathbb{C} \). Fix \( \tau \in \mathbb{N}_0 \) and corresponding integration constants \( \{e_j\}_{j=1,\ldots,r} \subset \mathbb{C} \). The aim in this section is to construct a solution \((u, v)\) of

\[
cBsq(u, v) = 0, \quad (u, v)|_{t_n = t_{0,n}} = (u^{(0)}, v^{(0)}).
\]

The function \( \varphi \) and the Baker–Akhiezer function \( \Psi \) associated with the classical Boussinesq hierarchy can be obtained as follows.

**Theorem 5.1.** Consider \( P = (z, y) \in \mathbb{C}^n \setminus \{F_{n+1}\} \) and \((z, x, x_0, t_0, t_0, r) \in \mathbb{C}^6\). Let \( \phi, \Psi, \) and \( S \) be given by (2.26), (3.23), and (4.12), respectively. Define

\[
\overline{\Psi} = \left[ \begin{array}{c} \Psi_1 \\ \Psi_2 \end{array} \right] = S \Psi, \quad \overline{\phi} = -\frac{\phi}{\tau}.
\]

Then \( \overline{\phi}(P, x, t_0) \) satisfies \( \overline{\Psi} = \overline{\Psi}/\overline{\phi} \) and

\[
v(x, t_0) \overline{\phi}(P, x, t_0) = -\frac{1}{2\alpha} \overline{\phi}^{-2}(P, x, t_0)
\]

\[
+ \frac{1}{2\alpha} (u(x, t_0) + \beta v(x, t_0)) \overline{\phi}(P, x, t_0)^2 - \frac{i}{\alpha} \overline{\phi}(P, x, t_0)^3 - \frac{1}{2\alpha} = 0,
\]

and \( \overline{\Psi}(z, x, x_0, t_0, t_0, r) \) fulfills

\[
\overline{\Psi}_z(P, x, x_0, t_0, t_0, r) = \overline{U}(z, x, t_0) \overline{\Psi}(P, x, x_0, t_0, t_0, r),
\]

\[
\overline{v}(P) \overline{\Psi}(P, x, x_0, t_0, t_0, r) = \overline{V}_{n+1}(z, x, t_0) \overline{\Psi}(P, x, x_0, t_0, t_0, r),
\]

\[
\overline{\Psi}_{t_0}(P, x, x_0, t_0, t_0, r) = \overline{V}_{r+1}(z, x, t_0) \overline{\Psi}(P, x, x_0, t_0, t_0, r).
\]
In addition, as long as the zeros of \( \mathcal{F}_n, x, t_r \) are all simple for \((x, t_r) \in \Omega, \Omega \subseteq \mathbb{R}^2 \) open and connected, \( \tilde{\Psi}, x, x_{0}, t, t_{0}, \) \((x, t_{r}), (x_{0}, t_{0}, r) \in \Omega, \) is meromorphic on \( \mathcal{K}_n \setminus \{P_{a, \pm}\} \).

Proof. Immediate from Theorem 2.1 and (4.1)–(4.6).

The explicit representation of algebro-geometric solutions of the classical Boussinesq hierarchy in terms of the Riemann theta function associated with \( K_n \) then reads as follows (we use the notation employed in Theorem 2.2).

**Theorem 5.2.** Let \( P \in \mathcal{K}_n \setminus \{P_{a, \pm}\}, (x, x_{0}, t, t_{0}) \in \mathbb{C}^4, \) assume \( K_n \) to be non-singular, and suppose \( D_{\tilde{\phi}(x, t_r)} \) and \( D_{\tilde{\phi}(x, t_{r})} \) to be nonspecial, that is, their index of speciality vanishes, \( \text{i}(D_{\tilde{\phi}(x, t_{r})}) = \text{i}(D_{\tilde{\phi}(x, t_{r})}) = 0. \) Moreover, suppose that \((u, v)\) satisfies \( \text{CB}_{\text{B}}(u, v) = 0 \) with \( (u, v)|_{x_{0} = t_{0}} = (v(0), 0(0)) \), a solution of the \( n \)th stationary classical Boussinesq system. Then the theta function representation of \((u, v)\) is given by

\[
 u(x, t_r) = c_{0, 0} + \frac{\partial}{\partial x} \ln \left( \frac{\theta(z_+ (\tilde{\phi}(x, t_r))))}{\theta(z_+ (\tilde{\phi}(x, t_r)))} \right), \\
 v(x, t_r) = -\frac{i}{\alpha} c_{0, 0} - \frac{\partial}{\partial z} \ln \left( \frac{\theta(z_+ (\tilde{\phi}(x, t_r))))}{\theta(z_+ (\tilde{\phi}(x, t_r)))} \right).
\]

(5.8)

Proof. Combine Theorem 2.2 and (4.18).

Obviously one can derive formulas similar to (2.63)–(2.65) for the functions \( \tilde{\phi} \) and \( \tilde{\Psi} \) using the explicit relation (5.3). We leave the corresponding details to the reader.

Algebro-geometric solutions of the time-dependent classical Boussinesq system \( \text{CB}_{\text{B}}(u, v) = 0 \) and their theta function representations were originally derived by Matveev and Yavor [27]. The case of real-valued solutions and additional reductions to elliptic solutions in the case of genus \( n \leq 3 \) were subsequently studied by Smirnov [31]. Theta function representations of algebro-geometric solutions of \( \text{CB}_{\text{B}}(u, v) = 0 \) in the case \( r = 3 \) appeared in a recent preprint by Geng and Wu [8].

**References**


DEPARTMENT OF MATHEMATICS, UNIVERSITY OF MISSOURI, COLUMBIA, MO 65211, USA
E-mail address: fristet@math.missouri.edu
URL: http://www.math.missouri.edu/people/fristet.html

DEPARTMENT OF MATHEMATICAL SCIENCES, NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY, N-7491 TRONDHEIM, NORWAY
E-mail address: holden@math.ntnu.no
URL: http://www.math.ntnu.no/~holden/
Det Kongelige Norske Videnskabers Selskab ble stiftet i 1760 og Skrifter utkom første gang i 1761. Det er en av verdens eldste vitenskapelige skriftserier som fremdeles utkommer.

The Royal Norwegian Society of Sciences and Letters was founded in 1760 and the Transactions (Skrifter) first appeared in 1761. The Transactions series is among the oldest scientific publications in the world.

© DKNVS/Tapir Academic Press 2000
ISBN 82-519-1570-8
ISSN 0368-6310
Printed in Norway by Tapir, Trondheim