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Jacobian Elliptic Function Calculation to the Nonlinear Equations Related to Lumped LC Networks

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Jacobian Elliptic Function Calculation
to the Nonlinear Equations Related to Lumped LC Networks

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(Synopsis)

A Self-dual and other network equations are derived through the transformations of the non­
linear difference-differential equations. The soliton train solutions of the former are obtained from
the elliptic function solutions of the latter by these transformations. The soliton train of the self­
dual network equation is found to be characterized by an arbitrary parameter $\theta$ in addition to the
wave number $\kappa$.

§1. Introduction

A discretized equation $\dot{N}_n = (N_{n-1} - N_{n+1}) \left( a + bN_n + cN_n^2 \right)$, considered as modelling
the corresponding continuum equation, is reduced through simple transformation to the following four types.

$$\dot{A}_n = (A_{n-1} - A_{n+1}) A_n, \quad \cdots \cdots (1)$$
$$\dot{B}_n = (B_{n-1} - B_{n+1}) B_n^2, \quad \cdots \cdots (2)$$
$$\dot{C}_n = (C_{n-1} - C_{n+1}) (1 - C_n^2), \quad \cdots \cdots (3)$$
$$\dot{D}_n = (D_{n-1} - D_{n+1}) (1 + D_n^2). \quad \cdots \cdots (4)$$

Equation (1), or the one-dimensional chain of Volterra competition equations finds its application in a model of energy transfer kinetics of Langmuir waves in plasma$^1$, in addition to its role as a model of a nonlinear electric network$^2$. Hirota's direct method was employed$^2$ for

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finding the $N$-soliton solution of this equation.

Equation (2) is one of the discrete analogue of KdV equation\(^3\)) and its application is found in a nonlinear lumped network\(^3\)). Hirota's direct method converts it to a single bilinear form\(^4\)).

Ablowitz and Ladik\(^5\)) succeeded in deducing eq. (3) and eq. (4) by discretizing the generalized Zakharov-Shabat formalism of inverse scattering, and showed their solution under the rapidly decaying initial condition at the infinity. The above restraint for the eqs. (3) and (4) was removed by Noguchi, Watanabe and Sakai\(^6\)), who showed their solutions for the nonvanishing initial condition at the infinity. Hirota and Satsuma\(^3\)) obtained an expression of the $N$-soliton solution to an extended ladder type network, which is reduced to the solutions of eq. (1) and eq. (3) with nonvanishing condition at the infinity.

Equation (4), first solved by Hirota\(^7\)), has more desirable property as a model of electric network as compared to eq. (3), while eq. (3) has its significance in relation to the equalities

$$A_n = B_{n-1/2} B_{n+1/2} = \left(1 - C_{n-1/2}\right) \left(1 - C_{n+1/2}\right). \quad \cdots \cdots (5)$$

We will explain in the next section the additional transformation relations with respect to the new quantities connecting eq. (2) and eq. (3).

Finally we refer to the Jacobian elliptic function solutions to eq. (1), eq. (2) and eq. (3) here, the derivation of which from a unified point of view is the main concern of this study. They are,

$$A_n = -\frac{\omega}{\text{sn} 2\kappa} \left[1 - k^2 \text{sn} \kappa \text{sn} 2\kappa \text{sn} \left(x + \frac{\kappa}{2}\right) \text{sn} \left(x - \frac{\kappa}{2}\right)\right], \quad \cdots \cdots (6)$$

$$B_n = \sqrt{-\frac{\omega}{2 \text{sn} \kappa \text{cn} \kappa \text{dn} \kappa}} \left[1 - k^2 \text{sn}^2 \kappa \text{sn}^2 x\right], \quad \cdots \cdots (7)$$

$$C_n = \frac{\text{sn} \kappa}{\text{cn} \kappa \text{dn} \kappa \text{sn} \theta} \left[\text{cn} \theta \text{dn} \theta + k^2 (\text{sn}^2 \theta - \text{sn}^2 \kappa) \text{sn} x \text{sn} \left(x + \theta\right)\right], \quad \cdots \cdots (8)$$

in which $x = \kappa n + \omega t$. In (6) and (7) $\kappa (0 < \kappa \leq K(k))$ and $\omega$ are arbitrary, and $\omega$ in a function of arbitrary $\kappa$ and $\theta (0 < \theta \leq K(k))$, given by

$$\omega = \frac{2 \text{sn} \kappa}{\text{cn} \kappa \text{dn} \kappa} \left(\frac{\text{sn}^2 \kappa}{\text{sn}^2 \theta} - 1\right). \quad \cdots \cdots (9)$$
§ 2. Transformations

(I) We start with a differential-difference equation

\[ \varphi_n = \coth(\varphi_{n-1} + \varphi_n) - \coth(\varphi_n + \varphi_{n+1}) \]  

\[ \cdots \quad (10) \]

Introducing \( P_n \) defined by \( P_n = \tanh\varphi_n \), we can express eq. (10) alternatively in the form

\[ \dot{P}_n = \left( \frac{1}{P_{n-1} + P_n} - \frac{1}{P_n + P_{n+1}} \right) \left( 1 - P_n^2 \right)^2 \]  

\[ \cdots \quad (11) \]

The transformation to the variables \( B_n \) and \( C_n \) is found to be given by

\[ B_n = \frac{2i}{\exp(-2\varphi_{n+\frac{1}{2}}) - \exp(2\varphi_{n-\frac{1}{2}})} \]  

\[ C_n = \coth(\varphi_{n-\frac{1}{2}} + \varphi_{n+\frac{1}{2}}) \]  

\[ \cdots \quad (12) \quad (13) \]

We will find the elliptic function solution to eq. (10) in § 3, where we use another expression of eq. (10) given by

\[ \dot{u}_n = 2P_n^{n+\frac{1}{2}} - P_n^{n-\frac{1}{2}} \]  

\[ \cdots \quad (14) \quad \text{and} \quad u_{n-\frac{1}{2}} + u_{n+\frac{1}{2}} = \cosh 2\varphi_n \]  

\[ \cdots \quad (15) \]

The direct substitution shows that \( u_n \) satisfies

\[ u_n = (u_{n-1} - u_{n+1}) (1 - C_n^2) \]  

\[ \cdots \quad (16) \]

(II) The next differential-difference equation that we investigate in § 3 is given by

\[ \frac{d}{d\ell} \tanh\psi_n = 4 \left[ \coth(\psi_{n-1} + \psi_n) - \coth(\psi_n + \psi_{n+1}) \right] \]  

\[ \cdots \quad (17) \]

Introducing \( Q_n \) defined by \( Q_n = \tanh\psi_n \), we can express eq. (17) alternatively in the form

\[ \dot{Q}_n = 4 \left( \frac{1}{Q_{n-1} + Q_n} - \frac{1}{Q_n + Q_{n+1}} \right) \left( 1 - Q_n^2 \right) \]  

\[ \cdots \quad (18) \]

In § 3 we seek the elliptic function solution of (18) using another representation

\[ \frac{v_n}{\bar{v}_n} = 4 \left( \frac{Q_n^{n-\frac{1}{2}} - Q_n^{n+\frac{1}{2}}}{Q_n^{n-\frac{1}{2}} + Q_n^{n+\frac{1}{2}}} \right) \]  

\[ \cdots \quad (19) \quad \text{and} \quad v_{n-\frac{1}{2}} v_{n+\frac{1}{2}} = \text{sech}^2\psi_n \]  

\[ \cdots \quad (20) \]

The transformation to the variables \( B_n \) and \( C_n \) is found to be given by

\[ B_n = \frac{2i\bar{v}_n}{Q_n^{n-\frac{1}{2}} + Q_n^{n+\frac{1}{2}}} \]  

\[ \cdots \quad (21) \quad \text{and} \quad C_n = \frac{2 + Q_n^{n-\frac{1}{2}} - Q_n^{n+\frac{1}{2}}}{Q_n^{n-\frac{1}{2}} + Q_n^{n+\frac{1}{2}}} \]  

\[ \cdots \quad (22) \]
The substitution shows that \( v_n \) and \( Q_n \) satisfy
\[
\dot{v}_n = (v_{n-1} - v_{n+1}) B_n^2, \quad \ldots \quad (23) \quad \text{and} \quad \dot{Q}_n = (Q_{n-1} - Q_{n+1}) A_n. \quad \ldots \quad (24)
\]

(III) We consider the elliptic function solution to an equation
\[
\dot{R}_n = \frac{1}{R_{n+1} + R_n} - \frac{1}{R_n + R_{n-1}}, \quad \ldots \quad (25)
\]
in the final part of § 3, where we use another representation
\[
\dot{w}_n = \frac{R_{n-1/2} - R_{n+1/2}}{R_{n-1/2} + R_{n+1/2}}, \quad \ldots \quad (26) \quad \text{and} \quad w_{n-1/2} + w_{n+1/2} = R_n^2. \quad \ldots \quad (27)
\]
The transformation to \( B_n \) is given by
\[
B_n = \frac{1}{R_{n+1/2} + R_{n-1/2}}, \quad \ldots \quad (28)
\]
and the substitution shows that \( w_n \) and \( R_n \) satisfy
\[
\dot{w}_n = (w_{n-1} - w_{n+1}) B_n^2, \quad \ldots \quad (29) \quad \text{and} \quad \dot{R}_n = (R_{n-1} - R_{n+1}) A_n. \quad \ldots \quad (30)
\]

§ 3. Elliptic Function Solutions

In this section we investigate the elliptic function solutions to the precedingly presented differential-difference equations.

In (i) we see that a postulated elliptic function solution to \( \exp 2\varphi_n \) and \( u_n \), proved to satisfy (15) in Appendix 1, can be transformed through (13) to the solution (8) to eq. (3). (9) is proved there by the comparison of the both sides of (3). Next we see that this solution is transformed to the elliptic function solutions of eqs. (2) and (1), formally equivalent to (7) and (6).

In (ii) we start with an assumption of an elliptic function solution to \( v_n \) and transform it to \( Q_n \) using relation (20). The substitution of them into the both sides of eq. (19) proves (9) again. We see that \( B_n \) and \( C_n \) obtained from \( v_n \) and \( Q_n \) coincide with the results found in (i).

In (iii) we assume an elliptic function solution to \( w_n \) and transform it to \( R_n \) using (27). The substitution of them to the both sides of (26) proves the validity of the assumption. \( R_n \) is transformed through (28) into the solution (7) for eq. (2).

(i) We postulate an elliptic function solution to eqs. (14) and (15) as follows,
\[
u_n = \frac{\text{sn} \kappa}{2 \sqrt{\text{sn}^2 \kappa - \text{sn}^2 \theta}} \left[ \text{cn} \theta \text{dn} \theta + k^2 \text{sn}^2 \theta \text{sn} \theta \text{sn} (x + \theta) \right] \quad \ldots \quad (31)
\]
Jacobian Elliptic Function Calculation

\[ J = \frac{1}{2} \sqrt{\frac{1 - \text{dn} \kappa_0}{2 (1 + \text{dn} \theta_0) (\text{dn} \theta_0 - \text{dn} \kappa_0)}} \left[ 2 \text{cn} \theta_0 - (1 - \text{dn} \theta_0) \cdot \frac{\text{dn}(x_0 + \frac{\theta_0}{2}) - \text{dn} \frac{\theta_0}{2}}{\text{dn}(x_0 + \frac{\theta_0}{2}) + \text{dn} \frac{\theta_0}{2}} \right], \tag{32} \]

and

\[ \exp 2 \varphi_n = \sqrt{\frac{\text{sn} \frac{1}{2} (\kappa_0 + \theta_0) \text{cn} \frac{1}{2} (\kappa_0 + \theta_0)}{\text{sn} \frac{1}{2} (\kappa_0 - \theta_0) \text{cn} \frac{1}{2} (\kappa_0 - \theta_0)}} \cdot \frac{\text{dn}(x_0 + \frac{\theta_0}{2}) + \frac{1}{2} (\theta_0 - \kappa_0)}{\text{dn}(x_0 + \frac{\theta_0}{2}) + \frac{1}{2} (\theta_0 + \kappa_0)}, \tag{33} \]

where \( x_0 = \kappa_0 n + \omega_0 t \) and \( \theta_0 \) and \( \kappa_0 \) are arbitrary. \( k, \theta, \kappa, \) and \( \omega \) are related to \( \kappa_0, \theta_0, \kappa_0 \)

and \( \omega_0 \) through a transformation of variable for elliptic functions

\[ k = \frac{1 - k_0'}{1 + k_0'}, \quad \theta = \frac{1}{2} (1 + k_0') \theta_0, \quad \kappa = \frac{1}{2} (1 + k_0') \kappa_0, \quad \text{and} \quad \omega = \frac{1}{2} (1 + k_0') \omega_0 (k_0' = \sqrt{1 - k_0^2}). \tag{34} \]

The proof that (32) and (33) satisfy eq. (15) is given in Appendix 1. (Equation (14) can be unused.) \( P_n \) is obtained from (33). Using an equality (A1–1) in Appendix 1, we find from (33),

\[ \exp 2(\varphi_n - \frac{1}{2} + \varphi_n + \frac{1}{2}) = \frac{[\text{dn}(\frac{\theta_0}{2} + \kappa_0) - \text{dn} \frac{\theta_0}{2}][\text{dn}(x_0 + \frac{\theta_0}{2}) + \text{dn}(\frac{\theta_0}{2} - \kappa_0)]}{[\text{dn}(x_0 + \frac{\theta_0}{2}) + \text{dn}(\frac{\theta_0}{2} + \kappa_0)]}, \tag{35} \]

Substituting (35) to (13) we find that \( C_n \) is given as

\[ C_n = \frac{1}{\text{dn} \frac{\theta_0}{2}[\text{dn}(\frac{\theta_0}{2} + \kappa_0) - \text{dn} \frac{\theta_0}{2} - \kappa_0)]} \cdot \left[ \text{dn}(\frac{\theta_0}{2} + \kappa_0) \text{dn}(\frac{\theta_0}{2} - \kappa_0) - \text{dn} \frac{\theta_0}{2} \right] \]

\[ \left[ - \text{dn}(\frac{\theta_0}{2} + \kappa_0) - \text{dn} \frac{\theta_0}{2} \right] \cdot \frac{\text{dn}(x_0 + \frac{\theta_0}{2}) - \text{dn} \frac{\theta_0}{2}}{\text{dn}(x_0 + \frac{\theta_0}{2}) + \text{dn} \frac{\theta_0}{2}} \right], \tag{36} \]

\[ = \frac{\text{sn} \kappa_0}{\text{cn} \kappa_0 \text{sn} \theta_0} \left[ \text{cn} \theta_0 + \frac{\text{dn} \theta_0 - \text{dn} \kappa_0}{1 + \text{dn} \kappa_0} \cdot \frac{\text{dn}(x_0 + \frac{\theta_0}{2}) - \text{dn} \frac{\theta_0}{2}}{\text{dn}(x_0 + \frac{\theta_0}{2}) + \text{dn} \frac{\theta_0}{2}} \right], \tag{37} \]

where (A2–3) in Appendix 2 can be used for the deformation (37) from (36). The transformation of variable (34) applied to (37) leads to the expression (8) for the elliptic function solution of (3).
Kazuaki NARITA

Now the substitution of (36) to the both sides of eq. (3) is found to require that the following condition is satisfied.

\[
\omega_0 = 8 \text{sn} \kappa_0 \text{cn} \kappa_0 \cdot \frac{\left[ \text{dn} \left( \frac{\theta_0 + \kappa_0}{2} \right) - \text{dn} \left( \frac{\theta_0}{2} \right) \right] \left[ \text{dn} \left( \frac{\theta_0 - \kappa_0}{2} \right) - \text{dn} \left( \frac{\theta_0}{2} \right) \right]}{\Delta \left( \frac{\theta_0}{2}, \kappa_0 \right) \left[ \text{dn} \left( \frac{\theta_0 + \kappa_0}{2} \right) - \text{dn} \left( \frac{\theta_0}{2} - \kappa_0 \right) \right]^2}
\]

\[
= \frac{4 \text{sn} \kappa_0}{\text{cn} \kappa_0} \cdot \frac{\text{dn} \theta_0 - \text{dn} \kappa_0}{(1 + \text{dn} \kappa_0)(1 - \text{dn} \theta_0)}
\]

where the definition of \( \Delta (\alpha, \beta) \) in (38) is given by (A1–2) in Appendix 1, and (A2–3) is used for the deformation (39) from (38). The transformation of variable (34) for the expression (39) leads to the formula (9).

Meanwhile the solution (33) for \( \exp 2\varphi_n \) is transformed to \( B_n \) as seen below.

\[
B_n = 2 \sqrt{\text{sn} \left( \frac{1}{2} \left( \theta_0 + \kappa_0 \right) \right) \text{cn} \left( \frac{1}{2} \left( \theta_0 + \kappa_0 \right) \right)} \cdot \frac{\text{dn} \left( \frac{\theta_0}{2} - \kappa_0 \right)}{\text{dn} \left( \frac{\theta_0}{2} + \kappa_0 \right)}
\]

\[
= 2 \sqrt{\varphi_1 \left( \frac{1}{2} \left( \theta'_0 + \kappa'_0 \right) \right) \varphi_2 \left( \frac{1}{2} \left( \theta'_0 + \kappa'_0 \right) \right) \varphi_3 \left( \frac{1}{2} \left( \theta'_0 - \kappa'_0 \right) \right) \varphi_4 \left( \frac{1}{2} \left( \theta'_0 - \kappa'_0 \right) \right)} \cdot \frac{\text{sn} \left( \frac{x_0 + \kappa_0}{2} \right) \text{cn} \left( \frac{x_0 + \kappa_0}{2} \right)}{\text{sn} \left( \frac{x_0 + \kappa_0}{2} \right) \text{cn} \left( \frac{x_0 + \kappa_0}{2} \right)}
\]

\[
= \frac{1}{\text{cn} \kappa_0 \sqrt{2 (1 + \text{dn} \kappa_0)(1 - \text{dn} \theta_0)}} \left[ 1 + \text{dn} \kappa_0 + (1 - \text{dn} \kappa_0) \frac{\text{dn} x_0 - 1}{\text{dn} x_0 + 1} \right]
\]

where' in (40) means the multiplication by \( \frac{1}{2K(k)} \). Further transformations (5) from \( B_n \) in (41) and \( C_n \) in (37) to \( A_n \) coincide with each other and give
Jacobian Elliptic Function Calculation

\[
A_n = 4 \frac{\varphi_1\left(\frac{1}{2}(\theta'_0 + \kappa'_0)\right) \varphi_2\left(\frac{1}{2}(\theta'_0 + \kappa'_0)\right) \varphi_3\left(\frac{1}{2}(\theta'_0 - \kappa'_0)\right) \varphi_4\left(\frac{1}{2}(\theta'_0 - \kappa'_0)\right) \varphi_5\left(\frac{\kappa'_0}{2}\right) \varphi_6\left(\frac{\kappa'_0}{2}\right)}{\varphi_1\left(\frac{\theta'_0}{2}\right) \varphi_2\left(\frac{\theta'_0}{2}\right) \varphi_3\left(\kappa'_0\right) \varphi_4\left(\kappa'_0\right)}
\]

\[
\cdot \frac{\varphi_3\left(\frac{x'_0}{2} + \frac{3}{4} \kappa'_0\right) \varphi_4\left(\frac{x'_0}{2} + \frac{3}{4} \kappa'_0\right) \varphi_5\left(\frac{x'_0}{2} - \frac{3}{4} \kappa'_0\right) \varphi_6\left(\frac{x'_0}{2} - \frac{3}{4} \kappa'_0\right)}{\varphi_3\left(\frac{x'_0}{2} + \frac{\kappa'_0}{4}\right) \varphi_4\left(\frac{x'_0}{2} + \frac{\kappa'_0}{4}\right) \varphi_5\left(\frac{x'_0}{2} - \frac{\kappa'_0}{4}\right) \varphi_6\left(\frac{x'_0}{2} - \frac{\kappa'_0}{4}\right)}
\]

\[
= \frac{2(dn \kappa_0 - dn \theta_0)}{cn^2 \kappa_0 (1 + dn \kappa_0)(1 - dn \theta_0)} \left[ \frac{dn \kappa_0 + cn \kappa_0 (1 - dn \kappa_0)}{dn x_0 - dn \frac{\kappa'_0}{2}} \right] . \quad \ldots (42)
\]

The transformation of variable (34) for (41) and (42) gives expressions equivalent to (7) and (6), in which \( \omega \) is replaced by a function of \( \kappa \) and \( \theta \) given by (9).

For the later convenience we remark here that the solution (37) for eq. (3) may be expressed as a sum of two functions of \( x_0 \) given by

\[
C_n = \frac{\text{sn} \kappa_0 \text{cn} \theta_0 (1 + dn \theta_0) (dn x_0 + dn \kappa_0)}{\text{sn} \theta_0 \text{cn} \kappa_0 (1 + dn \kappa_0) (dn x_0 + dn \theta_0)} + \frac{k_0^2 \text{sn} \kappa_0 (dn \kappa_0 - dn \theta_0) \text{sn} x_0 \text{cn} x_0}{cn \kappa_0 (1 + dn \kappa_0) (dn x_0 + 1) (dn x_0 + dn \theta_0)} . \quad \ldots (43)
\]

(43) is verified by the substitution of an equality

\[
\frac{dn(x_0 + \frac{\theta_0}{2}) - dn\frac{\theta_0}{2}}{dn(x_0 + \frac{\theta_0}{2}) + dn\frac{\theta_0}{2}} = \frac{cn \theta_0 (dn x_0 - 1)}{dn x_0 + dn \theta_0} - \frac{k_0^2 \text{sn} \theta_0 \text{sn} x_0 \text{cn} x_0}{(dn x_0 + 1) (dn x_0 + dn \theta_0)} \quad \ldots (44)
\]

to (37).

( ii ) We first assume that the elliptic function solution \( \nu_n \) satisfying eqs. (19) and (20) has a form

\[
\nu_n = \left[ \frac{\text{sn}^2 x - \text{sn}^2 \theta}{\text{sn} \kappa \text{cn} \theta \text{dn} \theta} \left[ 1 - k^2 \text{sn}^2 \theta \text{sn}^2 x \right] \right] \quad \ldots (45)
\]

\[
= \frac{1}{cn \theta_0 \sqrt{(1 + dn \theta_0)(1 - dn \kappa_0)} \text{dn} x_0 + dn \theta_0} \cdot \quad \ldots (46)
\]
Then the use of equality (A1–1) leads to

\[ v_n = \frac{1}{2} v_{n-1} \frac{1}{2} \]

\[ = -4 \left[ \frac{\operatorname{sd} \left( \frac{\theta_0 + \kappa_0}{2} \right) - \operatorname{sd} \left( \frac{\theta_0 - \kappa_0}{2} \right) \operatorname{sd} \left( \frac{\theta_0 - \kappa_0}{2} \right) - \operatorname{sd} \left( \frac{\theta_0 + \kappa_0}{2} \right)} \left[ \frac{\operatorname{sd} \left( \frac{\theta_0 + \kappa_0}{2} \right) - \operatorname{sd} \left( \frac{\theta_0 - \kappa_0}{2} \right) \right]^2 \right] \]

\[ \frac{\left[ \operatorname{sd} \left( \kappa_0 - \theta_0 \right) - \operatorname{sd} \left( \kappa_0 + \theta_0 \right) \right] \left[ \operatorname{sd} \left( \theta_0 - \kappa_0 \right) + \operatorname{sd} \left( \theta_0 + \kappa_0 \right) \right]} \left[ \frac{\operatorname{sd} \left( \theta_0 - \kappa_0 \right) + \operatorname{sd} \left( \theta_0 + \kappa_0 \right)} \right]^2 , \]

where (A2–3) is available for proving the deformation. (47) leads to the expression of \( Q_n \) as given below.

\[ Q_n = \frac{1}{\operatorname{cn} \left( \frac{\kappa_0}{2} + \theta_0 \right) - \operatorname{cn} \left( \frac{\kappa_0}{2} - \theta_0 \right)} \cdot \left[ \frac{\operatorname{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) \operatorname{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right) - \operatorname{dn} \left( \kappa_0 \right)} \right] \]

\[ \frac{- \left( \operatorname{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) - \operatorname{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right) \right) \left( \operatorname{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) - \operatorname{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right) \right)} \left[ \frac{\operatorname{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) - \operatorname{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right)} \right] \]

\[ \operatorname{dn} \left( \theta_0 - \frac{\kappa_0}{2} \right) \left( \operatorname{dn} \left( \theta_0 + \frac{\kappa_0}{2} \right) - \operatorname{dn} \left( \theta_0 - \frac{\kappa_0}{2} \right) \right) \]

\[ \cdot \frac{\operatorname{dn} \left( \theta_0 - \frac{\kappa_0}{2} \right) - \operatorname{dn} \left( \theta_0 + \frac{\kappa_0}{2} \right)} \left[ \frac{\operatorname{dn} \left( \theta_0 - \frac{\kappa_0}{2} \right) + \operatorname{dn} \left( \theta_0 + \frac{\kappa_0}{2} \right)} \right] \]
(51) can be proved by the use of (A1-1), and the derivation of (52) is given in Appendix 2. The substitution of (46), (51) and (52) to the both sides of eq. (19) proves that the assumption of the solution (46) is valid under the condition that (9) is satisfied. Also (46) and (52), and (51) and (52) are found to reproduce the expression (41) for $B_n$ and the expression (43) for $C_n$ respectively.

(iii) We assume that the elliptic function solution satisfying eqs. (26) and (27) is given as

$$ w_n = \frac{\text{sn} \kappa}{4 \omega \text{cn} \kappa \text{dn} \kappa} \left[ \text{sn}^2 \kappa - \text{dn}^2 \kappa - 2k^2 \text{sn}^2 \kappa \text{sn}^2 x \right] \quad \ldots (53) $$

Then we find that the relation (27) leads to

$$ R_n = \frac{1}{1+\text{dn} \kappa_0} \sqrt{\frac{\text{sn} \kappa_0}{2 \omega \text{cn} \kappa_0}} \left[ \frac{2 \text{cn} \kappa_0 - (1-\text{dn} \kappa_0)}{\text{dn} \kappa_0 + \text{dn} \kappa_0} \right] \quad \ldots (55) $$

(A2-4) applied to the expression (55) leads to

$$ R_{n+\frac{1}{2}} + R_{n-\frac{1}{2}} = \sqrt{-\frac{2 \text{sn} \kappa_0 \text{cn} \kappa_0}{\omega_0}} \cdot \frac{\text{dn} \kappa_0 + 1}{\text{dn} \kappa_0 + \text{dn} \kappa_0} \quad \ldots (57) $$

and the substitution of (57) and the time differential of (54) to the both sides of (26) proves the validity of the assumption (54). The transformation (28) and the transformation of variable (34) to the result leads to an elliptic function solution $B_n$ given by (7).

§ 4. Discussion

Since $\theta$ in the solution (8) is related to the mean level, the propagation velocity is a function of not only $\kappa$ but arbitrary $\theta$, as shown in (9). Also the amplitude and wave form is related to $\theta$, and the propagation velocity and the amplitude change their sign according as $\theta < \kappa$ or $\theta > \kappa$. Here we examine the extreme case in which $\theta = K(k)$. We find in this case

$$ C_n = k_1 \text{sn}(\kappa_1, k_1) \text{sn}(x_1, k_1) \quad \ldots (58) $$

and

$$ \omega = \omega_0 \equiv -2(1+k_1)\text{sn}(\kappa_1, k_1) \quad \ldots (59) $$

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Kazuaki NARITA

where \( k_1 = \frac{1 - k'}{1 + k'} \), \( \kappa_1 = (1 + k') \kappa \) and \( x_1 = (1 + k') x \).

\( \omega \) always satisfies the inequality \( \omega \geq \omega_0 \) in the solution (8) and in the related solutions such as \( B_n \) obtained from (41). The restriction seen in the latter is absent if we represent the solutions as (7) and (6).

Appendix 1

Using the following two equalities

\[
\Delta(u, w) \left[ \text{dn} (u + w) + \text{dn} v \right] \left[ \text{dn} (u - w) + \text{dn} v \right] \\
= \Delta(v, w) \left[ \text{dn} (v + w) + \text{dn} u \right] \left[ \text{dn} (v - w) + \text{dn} u \right], \quad \ldots \quad (A 1-1)
\]

in which

\[
\Delta(\alpha, \beta) = 1 - k_0^2 \text{sn}^2 \alpha \text{sn}^2 \beta, \quad \ldots \quad (A 1-2)
\]

and

\[
\text{dn} \left( x_0 + \frac{\theta_0}{2} + \frac{\kappa_0}{2} \right) \text{dn} \left( x_0 + \frac{\theta_0}{2} - \frac{\kappa_0}{2} \right) - \text{dn}^2 \frac{\theta_0}{2} = \frac{\epsilon_1 \text{dn}^2 \left( x_0 + \frac{\theta_0}{2} \right) + \epsilon_2}{\Delta \left( x_0 + \frac{\theta_0}{2}, \frac{\kappa_0}{2} \right)}, \quad \ldots \quad (A 1-3)
\]

in which

\[
\epsilon_1 = cn^2 \frac{\kappa_0}{2} \text{sn}^2 \frac{\theta_0}{2}, \quad \ldots \quad (A 1-4) \quad \epsilon_2 = k_0^2 \text{sn}^2 \frac{\kappa_0}{2} \text{dn}^2 \frac{\theta_0}{2} \text{cn}^2 \frac{\kappa_0}{2}, \quad \ldots \quad (A 1-5)
\]

we find that the assumption (32) leads to

\[
\frac{u_n - \frac{1}{2} + u_{n+\frac{1}{2}}}{2cn \theta_0 - \frac{\theta_0 + \kappa_0}{2}} = \frac{\left( 1 - \text{dn} \theta_0 \right) \left( \epsilon_1 \text{dn}^2 \left( x_0 + \frac{\theta_0}{2} \right) + \epsilon_2 \right)}{\Delta \left( \frac{\theta_0}{2}, \frac{\kappa_0}{2} \right) \left( \text{dn} \left( x_0 + \frac{\theta_0}{2} \right) + \text{dn} \frac{1}{2} \left( \theta_0 + \kappa_0 \right) \right) \left( \text{dn} \left( x_0 + \frac{\theta_0}{2} \right) + \text{dn} \frac{1}{2} \left( \theta_0 - \kappa_0 \right) \right)}.
\]

\[
\ldots \quad (A 1-6)
\]
On the other hand, using an equality
\[
\frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 \pm \theta_0 \right) = \frac{\epsilon_1 \text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) + \epsilon_2}{2 \kappa_0^2 \text{sn} \frac{1}{2} \left( \kappa_0 \pm \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 \pm \theta_0 \right)}, \quad \cdots \quad (A1-7)
\]
we find that the assumption (33) leads to
\[
\cosh 2\varphi_n = \frac{1}{4 \kappa_0^2 \text{sn} \frac{1}{2} \left( \kappa_0 \pm \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 \pm \theta_0 \right) \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right)}{\sqrt{\left( \text{sn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \right)^2}} \cdot \left[ 2 \left( \epsilon_1 \text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) + \epsilon_2 \right) \right.
\]
\[
\left. + \frac{(\text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) - \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right))^2(\epsilon_1 \text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) + \epsilon_2)}{(\text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) + \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right)) (\text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) + \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right))} \right]. \quad \cdots \quad (A1-8)
\]
Substituting two equalities
\[
\frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \\
= \frac{2 \kappa_0^2 \text{sn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right)}{\left[ \text{dn} \left( \frac{\theta_0}{2}, \frac{\kappa_0}{2} \right) \right]^2} \cdot \frac{\text{dn} \theta_0 - \text{dn} \kappa_0}{(1 - \text{dn} \theta_0)(1 - \text{dn} \kappa_0)}, \quad \cdots \quad (A1-9)
\]
\[
\epsilon_1 \text{dn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{dn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) + \epsilon_2 \\
= \frac{4 \kappa_0^2 \text{cn} \theta_0 \text{sn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 + \theta_0 \right) \text{sn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right) \text{cn} \frac{1}{2} \left( \kappa_0 - \theta_0 \right)}{\text{sn} \theta_0 \cdot \left[ \text{dn} \left( \frac{\theta_0}{2}, \frac{\kappa_0}{2} \right) \right]^2}, \quad \cdots \quad (A1-10)
\]
and the difference formula of dn to (A1-8), we can verify the coincidence of two expressions (A1-6) and (A1-8).

Appendix 2

From (48) we find
\[
Q_{n-\frac{1}{2}} + Q_{n+\frac{1}{2}} = \frac{1}{\text{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) - \text{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right)} \left[ \text{dn} \left( \frac{\kappa_0}{2} + \theta_0 \right) + \text{dn} \left( \frac{\kappa_0}{2} - \theta_0 \right) - 2 \text{dn} \frac{\kappa_0}{2} \right]
\]
Kazuaki NARITA

\[ + (\text{dn}(\frac{K_0}{2} + \theta_0) - \text{dn}(\frac{K_0}{2} - \theta_0)) (\text{dn}(\frac{K_0}{2} + \theta_0) - \text{dn}(\frac{K_0}{2} - \theta_0)) \]

\[ \cdot \frac{(\text{dn}(x_0 + \frac{K_0}{2}) + \text{dn}(x_0 - \frac{K_0}{2}) + 2 \text{dn}(\frac{K_0}{2}))}{(\text{dn}(x_0 + \frac{K_0}{2}) + \text{dn}(\frac{K_0}{2})) (\text{dn}(x_0 - \frac{K_0}{2}) + \text{dn}(\frac{K_0}{2}))} \] \quad \cdots (A2-1)

We obtain (50) by substituting the following three equalities to (A2-1), i.e.,

\[ \frac{\text{dn}(\frac{K_0}{2} + \theta_0) + \text{dn}(\frac{K_0}{2} - \theta_0) - 2 \text{dn}(\frac{K_0}{2})}{\text{dn}(\frac{K_0}{2} + \theta_0) - \text{dn}(\frac{K_0}{2} - \theta_0)} = \frac{\text{sn} \theta_0 [\text{cn} \theta_0 + \text{dn} \theta_0]}{\text{sn} \theta_0 \text{cn} \theta_0 (1 + \text{dn} \theta_0)} , \quad \cdots (A2-2) \]

\[ \frac{(\text{dn}(\frac{K_0}{2} + \theta_0) - \text{dn}(\frac{K_0}{2} - \theta_0))(\text{dn}(\frac{K_0}{2} - \theta_0) - \text{dn}(\frac{K_0}{2})}{\text{dn}(\frac{K_0}{2} + \theta_0) - \text{dn}(\frac{K_0}{2} - \theta_0))} = \frac{\text{dn}(\frac{K_0}{2}) \text{sn} \theta_0 (\text{dn} \theta_0 - \text{dn} \kappa_0)}{\text{sn} \theta_0 \text{cn} \theta_0 (1 + \text{dn} \theta_0)} , \quad \cdots (A2-3) \]

\[ \frac{\text{dn}(x_0 + \frac{K_0}{2}) + \text{dn}(x_0 - \frac{K_0}{2}) + 2 \text{dn}(\frac{K_0}{2})}{(\text{dn}(x_0 + \frac{K_0}{2}) + \text{dn}(\frac{K_0}{2}) (\text{dn}(x_0 - \frac{K_0}{2}) + \text{dn}(\frac{K_0}{2}))} = \frac{\text{sn} \kappa_0 [\text{cn} \kappa_0 \text{dn} x_0 + \text{dn} \kappa_0 + \text{cn} \kappa_0]}{\text{sn} \kappa_0 \text{cn} \kappa_0 (1 + \text{dn} \kappa_0) (\text{dn} x_0 + \text{dn} \kappa_0)} . \quad \cdots (A2-4) \]

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