Research Article

Analytical and Numerical Methods for the CMKdV-II Equation

Ömer Akin¹ and Ersin Özuğurlu²

¹ Department of Mathematics, TOBB University of Economics and Technology, Sogutozu Street No: 43, Sogutozu, 06560 Ankara, Turkey
² Department of Mathematics and Computer Sciences, Faculty of Arts and Sciences, University of Bahcesehir, Besiktas, 34353 Istanbul, Turkey

Correspondence should be addressed to Ersin Özuğurlu, ersin.ozugurlu@bahcesehir.edu.tr

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Hirota’s bilinear form for the Complex Modified Korteweg-de Vries-II equation (CMKdV-II) $U_t - 6|U|^2U_x + U_{xxx} = 0$ is derived. We obtain one- and two-soliton solutions analytically for the CMKdV-II. One-soliton solution of the CMKdV-II equation is obtained by using finite difference method by implementing an iterative method.

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1. Introduction

It has been known that quasilinear parabolic equations or non-linear reaction-diffusion systems arise in physics, chemistry, biology, and other applied sciences. The following three equations are the examples of this type of partial differential equations (PDEs). First one is called the Korteweg-de Vries equation

$$U_t + cUU_x + U_{xxx} = 0,$$

and first encountered in the study of waters, Korteweg [1], denoted by KdV. The other is called the Complex Modified Korteweg-de Vries-I equation (CMKdV-I)

$$U_t + \alpha \left( |U|^2 U \right)_x + \beta U_{xxx} = 0,$$
which arises both in the asymptotic investigation of electrostatic waves in a magnetized plasma and in the asymptotic investigation of one-dimensional plane-wave propagation in a micropolar medium, Erbay [2]. The last one is the Complex Modified Korteweg-de Vries-II equation (CMKdV-II)

\[ U_t - 6|U|^2U_x + U_{xxx} = 0, \]  
(1.3)

which is another example for quasilinear parabolic equations or non-linear reaction-diffusion systems, Ablowitz [3]. Equation (1.2) does not hold the Painlevé property but the (1.1) and (1.3) do, Mohammad [4]. The equations which have Painlevé property may be solved by the method of Inverse Scattering Transformations (IST) and hence they are completely integrable [5, 6]. Sometimes it is not easy to solve IST problems [3], such as for CMKdV-II equation. Therefore the need for an easy and useful method which has to give soliton solutions for a given PDE is emerged. An important method is developed by Hirota for finding N-soliton solutions of non-linear PDE [5, 6].

In this paper, the Hirota’s method is applied to the CMKdV-II equation. The Hirota’s method generally requires the transformation of PDE into homogeneous bilinear forms of degree two. Only specific PDEs can be transformed in this way. This means, when a bilinear (form) equation can be solved, then N-parameter solution can be obtained as a series which self-truncates at finite length. These expansions that self-truncate in this way give automatically exact solutions. Self-truncation, however, does not occur for all bilinear equations; if it does, then the equation in question possesses multiple soliton solutions. The reason for this situation has never been adequately explained. In other words, self-truncation which is equivalent to complete integrability would require a connection with the conserved quantities of the original equation.

In this study, it is proven that the CMKdV-II equation has self-truncated Hirota expansions. It is shown that there is a direct equivalence between the N-soliton solutions of Hirota’s bilinear form of CMKdV-II and the Backlund transformations proposed by Weiss, Tabor, and Carnevale [7, 8].

Now, the question here is where the soliton comes from. Firstly, J. S. Russel in 1834 recorded his observations of great solitary wave as a mean of developing the mathematical properties of a large class of solvable non-linear evolution equations. Solitary waves, solitons, Backlund transformations, conserved quantities and integrable evolutions which can be also named as completely integrable Hamiltonian systems are in the class of solvable non-linear evolution equations. The description of John Scott Russel has aroused among mathematicians and physicists one hundred and forty years later, Zabusky [9]. In their paper, they were the first ones who defined the solution for the following KdV equation:

\[ U_t + 6UU_x + U_{xxx} = 0. \]  
(1.4)

For the CMKdV-II Equation, the Hirota’s bilinear form is given in Section 2 and the analytical one- and two-soliton solutions are presented in Section 3. The numerical procedure and results for one-soliton solution are outlined in Section 4.
2. Hirota’s Bilinear Form of the CMKdV-II Equation

It is known that the equation

$$U_t - 6|U|^2U_x + U_{xxx} = 0$$  \hspace{1cm} (2.1)

is the complex modified Korteweg de Vries II equation (CMKdV-II). Let $g$ and $f$ be the complex and real valued functions, respectively, satisfying

$$U = \frac{g}{f}, \quad |g|^2 = -ff_{xx} + f_x^2.$$  \hspace{1cm} (2.2)

By using the transformation above, CMKdV-II becomes

$$fg_t - f_tg + 3(f_{xx}g_x - f_xg_{xx}) + fg_{xxx} - gf_{xxx} = 0.$$  \hspace{1cm} (2.3)

Let

$$D_x = \frac{\partial}{\partial x} - \frac{\partial}{\partial x'}, \quad D_t = \frac{\partial}{\partial t} - \frac{\partial}{\partial t'}$$

then (2.3) becomes

$$\left[ D_x^3 + D_t \right] g(x, t) f(x', t') \bigg|_{x' = x, t' = t} = 0 \iff \left( D_x^3 + D_t \right) g f = 0,$$

which is a homogeneous bilinear form and called Hirota’s form of CMKdV-II equation. Let

$$U = \frac{U_0}{\Phi} + U_1$$

be the truncated solution of CMKdV-II. Then

$$|U_0|^2 = \Phi_x^2,$$

$$\overline{U_0}U_1 + \overline{U_1}U_0 = -\Phi_{xx},$$

$$6U_{0xx}|U_1|^2 - 6\Phi_{xx}U_{1x} = U_{0xxx} + U_{0tt},$$

$$6\Phi_xU_0|U_1|^2 - 6\Phi_x^2U_{1x} = 3(\Phi_xU_{0xx} - \Phi_{xx}U_{0x}) + U_0(\Phi_{xxx} + \Phi t),$$

$$U_{1t} - 6|U_1|^2U_{1x} + U_{1xxx} = 0.$$  \hspace{1cm} (2.7)
Here $U$ and $U_1$ are both separated solutions of the CMKdV-II equation. Hence it is an onto Backlund transformation of CMKdV-II equation. The system of these equations are called the Painlevé relations. There is a relation between the soliton of the bilinear (2.5) and the function $\Phi$ of the Painlevé relations (2.7). Consider the solitons

$$U = \frac{g}{f},$$

$$U_1 = \frac{g^{(1)}}{f^{(1)}}$$

having the properties

$$|U|^2 = (\log f)_{xx},$$

$$|U|^2 = -\frac{\partial^2}{\partial x^2} \log \Phi + |U_1|^2.$$  (2.9)

It can be shown that

$$f = \Phi f^{(1)}, \quad g = U_0 f^{(1)} + \Phi g^{(1)}. $$  (2.10)

**Theorem 2.1.** If $f^{(n)}$ and $g^{(n)}$ satisfy (2.5) for all $n$, with

$$|g^{(n)}| = f^{(n)} f^{(n)}_{xx} - \left(f^{(n)}_x \right)^2, $$  (2.11)

and if

$$f^{(n)} = \Phi^{(n-1)} f^{(n-1)},$$

$$g^{(n)} = U_0 f^{(n-1)} + \Phi^{(n-1)} g^{(n-1)}, $$  (2.12)

then the resulting equations in $\Phi_{n-1}, U_0$ and $U^{(n-1)}$ are satisfied by the Painlevé relations (2.7). Furthermore

$$f^{(n)} = \prod_{i=0}^{n-1} \Phi_i, $$  (2.13)

with

$$f^{(0)} = 1.$$  (2.14)

**Proof.** When substituting (2.12) into (2.5) and using the Painlevé relations when necessary yields the claim of the theorem. Using (2.12) successively we obtain the relation (2.13) that completes the proof of the theorem [4].

□
3. Solitons for the CMKdV-II Equation

By using the usual perturbation method, $N$-parameter exact solitary wave solutions of (7) can be obtained, Nayfeh [10]. The power series of $g$ and $f$ which are given in Hirota [11] in a small parameter $\varepsilon$ are:

$$g = \varepsilon g^{(1)} + \varepsilon^3 g^{(3)} + \varepsilon^5 g^{(5)} + \cdots$$

$$f = 1 + \varepsilon^2 f^{(2)} + \varepsilon^4 f^{(4)} + \cdots$$

(3.1)

where $g$ and $f$ are the solutions of the (2.5). Then considering the increasing powers of $\varepsilon$ from (2.5) it is clear that

$$g^{(1)}_{xxx} + g^{(1)}_t = 0,$$

(3.2)

$$g^{(3)}_{xxx} + g^{(3)}_t = -(D_x^3 + D_t) f^{(2)} g^{(1)},$$

(3.3)

$$g^{(5)}_{xxx} + g^{(5)}_t = -(D_x^3 + D_t) \left[f^{(4)} g^{(1)} + f^{(2)} g^{(3)}\right],$$

(3.4)

$$g^{(5)}_{xxx} + g^{(5)}_t = -(D_x^3 + D_t) \left[f^{(6)} g^{(1)} + f^{(4)} g^{(3)} + f^{(2)} g^{(5)}\right]$$

(3.5)

and (2.2) yields

$$f^{(2)}_{xx} = -g^{(1)} g^{(1)*},$$

(3.6)

$$f^{(4)}_{xx} = -g^{(1)} g^{(3)*} - g^{(1)*} g^{(3)} - f^{(2)} f^{(2)} - f^{(2)} f^{(2)*},$$

(3.7)

$$f^{(6)}_{xx} = -g^{(3)} g^{(5)*} - g^{(1)} g^{(5)*} - 2 f^{(2)} f^{(4)} f^{(2)*} - f^{(4)} f^{(2)} f^{(2)},$$

(3.8)

where * stands for the complex conjugate.

3.1. One-Soliton Solution for the CMKdV-II Equation

To obtain one-soliton solution of the CMKdV-II equation, let’s take

$$g^{(1)} = e^{\Phi + i\Psi}; \quad \Phi + i\Psi = a_1 x + b_1 t + c_1.$$ 

(3.9)
Hence

\[
\begin{align*}
a_1 &= \text{re}(a_1) + I \cdot \text{im}(a_1), \\
b_1 &= \text{re}(b_1) + I \cdot \text{im}(b_1), \\
c_1 &= \text{re}(c_1) + I \cdot \text{im}(c_1), \\
\text{re}(b_1) &= -(\text{re}(a_1))^3 + 3 \cdot \text{re}(a_1) - (\text{im}(a_1))^2, \\
\text{im}(b_1) &= (\text{re}(a_1))^3 - 3 \cdot \text{im}(a_1) - (\text{re}(a_1))^2, \\
f^{(2)} &= \frac{e^{2\Phi}}{4(\text{re}(a_1))^2},
\end{align*}
\]

and \(f^{(2n)} = 0, g^{(2n-1)} = 0\) for all \(n \geq 2\) where \(I\) stands for the complex number \(i\). Therefore

\[
f(t, x) = 1 + \frac{e^{2\Phi}}{4(\text{re}(a_1))^2} e^{2\Phi}, \quad g(x, t) = e^{\Phi_1 + I\Psi_1}
\]

is a solution of Hirota bilinear form (2.5) and

\[
U = \frac{g(x, t)}{f(x, t)}
\]

is the corresponding one-soliton solution of the CMKdV-II equation.

### 3.2. Two-Soliton Solution for the CMKdV-II Equation

To find two-soliton solution, let’s take

\[
g^{(1)} = e^{\Phi_1 + I\Psi_1} + e^{\Phi_2 + I\Psi_2},
\]

where

\[
\begin{align*}
\Phi_1[t, x] &= \text{re}(a_1) \ast x + \text{re}(b_1) \ast t + \text{re}(c_1) \\
\Psi_1[t, x] &= \text{im}(a_1) \ast x + \text{im}(b_1) \ast t + \text{im}(c_1) \\
\Phi_2[t, x] &= \text{re}(a_2) \ast x + \text{re}(b_2) \ast t + \text{re}(c_2) \\
\Psi_2[t, x] &= \text{im}(a_2) \ast x + \text{im}(b_2) \ast t + \text{im}(c_2)
\end{align*}
\]
with

\[
\begin{align*}
\text{re}(b_1) &= -(\text{re}(a_1))^3 + 3 \cdot \text{re}(a_1) - (\text{im}(a_1))^2 \\
\text{im}(b_1) &= (\text{re}(a_1))^3 - 3 \cdot \text{im}(a_1) - (\text{re}(a_1))^2 \\
\text{re}(b_2) &= -(\text{re}(a_2))^3 + 3 \cdot \text{re}(a_2) - (\text{im}(a_2))^2 \\
\text{im}(b_2) &= (\text{re}(a_2))^3 - 3 \cdot \text{im}(a_2) - (\text{re}(a_2))^2.
\end{align*}
\] (3.15)

Hence from (3.8), it can immediately be found that

\[
f^{(2)} = \frac{e^{2\Phi_1}}{4(\text{re}(a_1))^2} + \frac{e^{2\Phi_2}}{4(\text{re}(a_2))^2}.
\] (3.16)

Since the right hand side of (3.3) is not zero, a special solution for $g^{(3)}$ can be found by the method of undetermined coefficients. Considering (3.7), $f^{(4)}_{xx}$ is a nonzero real function. The right hand side of (3.4) is not zero, and we can take $g^{(5)} = 0$. From (3.8), it is seen that $f^{(6)}_{xx}$ is zero and that $f^{(6)} = 0$ is taken for convenience. Further computations have shown that

\[
f^{(2n)} = 0, \quad g^{(2n-1)} = 0, \quad n \geq 3.
\] (3.17)

Hence

\[
f[t,x] = 1 - \frac{1}{4(\text{re}(a_1))^2}e^{2\Phi_1[t,x]} - \frac{1}{4(\text{re}(a_2))^2}e^{2\Phi_2[t,x]}
\]
\[
+ \frac{1}{16(\text{re}(a_1))^2(\text{re}(a_2))^2} \frac{(\text{im}(a_1) - \text{im}(a_2))^2 + (\text{re}(a_1) - \text{re}(a_2))^2}{(\text{im}(a_1) - \text{im}(a_2))^2 + (\text{re}(a_1) - \text{re}(a_2))^2} e^{2(\Phi_1[t,x] + \Phi_2[t,x])}
\]
\[
- \frac{1}{[\text{re}(a_1) + I \cdot (\text{im}(a_1) - \text{im}(a_2)) + \text{re}(a_2)]^2} e^{\Phi_1[t,x] + \Phi_2[t,x] + I \Psi_1[t,x] - I \Psi_2[t,x]}
\]
\[
- \frac{1}{[\text{re}(a_1) + I \cdot (\text{im}(a_1) - \text{im}(a_2)) + \text{re}(a_2)]^2} e^{\Phi_1[t,x] + \Phi_2[t,x] - I \Psi_1[t,x] + I \Psi_2[t,x]}
\]

\[
g[t,x] = e^{\Phi_1[t,x] + \Phi_2[t,x] + I \Psi_1[t,x] + I \Psi_2[t,x]}
\]
\[
+ \frac{(-I \cdot \text{im}(a_1) - \text{re}(a_1) + I \cdot \text{im}(a_2) + \text{re}(a_2))^2}{[2\text{re}(a_2)(\text{im}(a_1) - I \cdot \text{re}(a_1) - \text{im}(a_2) + I \cdot \text{re}(a_2))]} e^{\Phi_1[t,x] + 2\Phi_2[t,x] + I \Psi_1[t,x]}
\]
\[
+ \frac{(-I \cdot \text{im}(a_1) - \text{re}(a_1) + I \cdot \text{im}(a_2) + \text{re}(a_2))^2}{[2\text{re}(a_2)(\text{im}(a_1) - I \cdot \text{re}(a_1) - \text{im}(a_2) + I \cdot \text{re}(a_2))]} e^{2\Phi_1[t,x] + \Phi_2[t,x] + I \Psi_2[t,x]}
\] (3.18)
Table 1: The difference of two consecutive solution values (N = 256, −128 ≤ x ≤ 128, M = 500, 0 ≤ t ≤ 5).

<table>
<thead>
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<th>Δx</th>
<th>Δt</th>
<th>L_2</th>
<th>L_∞</th>
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<td>1.0</td>
<td>0.01</td>
<td>0.1410966549</td>
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<td>0.0105278461</td>
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is a solution of the Hirota’s bilinear equation (2.5) and

\[ w = \frac{g(x, t)}{f(x, t)} \quad (3.19) \]

is the corresponding two-soliton solution of the CMKdV-II (1.3). Similarly, it is possible to find \( N \) solitary wave solutions by taking

\[ g^{(N)} = \sum_{i=1}^{n} e^{a_i x + b_i t + c_i}, \quad (3.20) \]

where

\[ b_i = -a_i^3 \quad (3.21) \]

but the computations are very tedious for \( i > 3 \).

4. Numerical results

4.1. Iterative Methods Using Finite Difference Schemes

Previously many researchers have used the finite difference methods to solve the KdV equation, Feng [12]. In the last decade, the CMKdV-II type equations were solved numerically by using split-step Fourier method [13–15]. Also parallel implementation of the split-step Fourier method using Fast Fourier Transform (FFT) has been studied by Taha [16] (see references therein). Here, in this work, the one-soliton solution of the CMKdV-II equation is considered. A finite interval for our numerical purposes is subjected, namely, \([a, b]\). The constants \( a \) and \( b \) can be chosen sufficiently large so that the boundaries do not affect the propagation of solitons. For the CMKdV-II (1.3), a numerical (finite difference) method of solution using iterative method is introduced. \( U_t \) is approximated by using forward time difference scheme, \( U_x \) and \( U_{xxx} \) by the central-space difference scheme using four-points. Equation (1.3) becomes

\[
\left( \frac{z_{m+1} - z_m}{\Delta t} \right) - 6\left| z_m \right|^2 \left[ \frac{-z_{m+2} + 8z_{m+1} - z_{m+1} + z_{m-1}}{12\Delta x} \right] + \left[ \frac{z_{m+1} - 2z_{m+1} + 2z_{m-1} - z_{m-2}}{2(\Delta x)^3} \right] = 0,
\]

(4.1)

where \( z_m = z(t_n, x_m) = z(nk, mh), k = \Delta t, h = \Delta x \).
Multiplying both sides by $2(\Delta x)^3$ and rearranging the terms we get

\[
\begin{align*}
    z_{m+1}^{n+1} & \left[ 1 + 6(\Delta x)^2 \left( |z_m^{n-1}|^2 \right) \right] + z_{m+1}^{n+1} \left[ -2 - 48(\Delta x)^2 |z_m^{n-1}|^2 \right] \\
    + z_m^{n+1} \left[ \frac{2(\Delta x)^2}{\Delta t} \right] + z_m^{n+1} \left[ 2 + 48(\Delta x)^2 \left( |z_m^{n-1}|^2 \right) \right] \\
    + z_m^{n+1} \left[ -1 - 6(\Delta x)^2 \left( |z_m^{n-1}|^2 \right) \right] &= \frac{2(\Delta x)^3}{\Delta t} z_m^n
\end{align*}
\]  

for $3 \leq m \leq N - 2$. For $m = N - 1$ and $m = N$, the backward difference scheme is chosen in $U_x$ and $U_{xxx}$. Three more equations come from the boundary conditions, namely, $U(a) = 0$, $U(b) = 0$, and $\partial U / \partial x = 0$ at $x = a$. Thus, $N$ unknowns, namely, $z_i^{n+1}$, $i = 1, \ldots, N$ and $N$ equations are obtained. Since the value of the non-linear term is known here, a system of linear equations is obtained. The initial guess is taken as $U(x,0) = \sqrt{2c/\alpha} \text{sech}\left(\sqrt{c}(x-x_0)\right)e^{i\theta_0}$ which represents a solitary wave initially at $x_0$ moving to the right with velocity $c$ and $\theta_0$ is the polarization angle. The main idea is to assume that the non-linear term $|z_m^{n-1}|^2$ is zero first and then solve the problem for whole time domain. Afterwards, this solution is taken and substituted for the non-linear term and solved again iteratively. The following two norms, namely, $L_\infty$ and $L_2$ are used to measure the accuracy of the approximate solutions for stopping criteria. These norms are defined as following:

\[
L_\infty = \max_n(||\tilde{z}_n| - |z_n||), \quad L_2 = \sqrt{\sum_n (||\tilde{z}_n| - |z_n||)^2},
\]

where $\tilde{z}_n$ and $z_n$ are the two consecutive new and old approximate solutions, respectively, at point $(n\Delta x, T)$ for all $n$, where $T$ is the final or terminating time. FORTRAN and MATLAB are used to obtain the results and figures, respectively. The graph of one-soliton numerical solution is shown in Figure 1.
5. Conclusions

In this study, Hirota’s bilinear form for the complex modified Korteweg-de Vries-II equation is derived. One- and two-soliton solutions of the CMKdV-II equation are obtained analytically. One-soliton solution of the CMKdV-II equation is obtained by using finite difference method by implementing an iterative method. The computational cost is due to only finding the inverse of the matrix. The difference of two consecutive solution values according to the formula which is given in (4.3) is shown in Table 1 result. The convergence rate in the method presented above is quadratic as it can be seen in Table 1 result. It would be interesting to see what happens if this numerical scheme for the interaction of two-soliton waves for the CMKdV-II equation is applied. The numerical scheme deserves further study according to its application to the CMKdV-II equation.

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References


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Lead Guest Editor

Teodor Bulboaca, Faculty of Mathematics and Computer Science, Babes-Bolyai University, 400084 Cluj-Napoca, Romania; bulboaca@math.ubbcluj.ro

Guest Editors

Mohamed K. Aouf, Department of Mathematics, Faculty of Science, University of Mansoura, Mansoura 35516, Egypt; mkaouf127@yahoo.com

Nak Eun Cho, Department of Applied Mathematics, Pukyong National University, Busan 608-737, South Korea; necho@pknu.ac.kr

Stanisława R. Kanas, Department of Mathematics, Rzeszów University of Technology, 35-959 Rzeszów, Poland; skanas@prz.rzeszow.pl

Milutin Obradović, Department of Mathematics, Faculty of Civil Engineering, Belgrade University, Belgrade, Serbia; obrad@grf.bg.ac.yu
Special Issue on
Takahashi’s Legacy in Fixed Point Theory

Call for Papers

On March 31, 2009, Professor Wataru Takahashi will be retiring from the Tokyo Institute of Technology. Among his many fundamental contributions to nonlinear analysis, the existence theorems for noncommutative families of nonexpansive mappings, convergence theorems for generalized nonexpansive mappings, and fixed point theorems in Banach, topological vector, and metric spaces have proved to be of remarkable value. In fact, researchers continue extending his results aggressively. There cannot be any better time than this moment to dedicate this special issue in his honor.

Subjects connected with his theory, such as the following, will be welcome:

- Existence of fixed points for (families of) (generalized) nonexpansive mappings and others
- Approximations to fixed points (or zeros) of (generalized) nonexpansive mappings, monotone mappings, and others
- Fixed point theorems in topological vector spaces
- Fixed point theorems in (convex) metric spaces
- Invariant means and nonlinear analysis
- Theories and applications around the above

Before submission authors should carefully read over the journal’s Author Guidelines, which are located at http://www.hindawi.com/journals/fpta/guidelines.html. Articles published in this special issue shall be subject to a reduced Article Processing Charge of €200 per article. Prospective authors should submit an electronic copy of their complete manuscript through the journal Manuscript Tracking System at http://mts.hindawi.com/ according to the following timetable:

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Guest Editors

**Anthony To-Ming Lau**, Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, Alberta, Canada T6G-2G1; tlau@math.ualberta.ca

**Tomonari Suzuki**, Department of Basic Sciences, Kyushu Institute of Technology, Tobata, Kitakyushu 804-8550, Japan; suzuki-t@mns.kyutech.ac.jp