Investigation of a Unified Chaotic System and Its Synchronization by Simulations

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We investigate a unified chaotic system and its synchronization including feedback synchronization and adaptive synchronization by numerical simulations. We propose a new dynamical quantity denoted by $K$, which connects adaptive synchronization and feedback synchronization, to analyze synchronization schemes. We find that $K$ can estimate the smallest coupling strength for a unified chaotic system whether it is complete feedback or one-sided feedback. Based on the previous work, we also give a new dynamical method to compute the leading Lyapunov exponent.

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Chaos is a typical nonlinear phenomenon, and its general feature is that the solution of a chaotic system is extremely sensitive to initial conditions. Since Lorenz discovered the first chaotic system, many chaotic systems have been discovered and studied.1-3 Liu and Chen proposed a unified chaotic system,4 which connects the Lorenz system with the Chen system. A unified chaotic system has many good features,2,4,5 and they have been widely investigated.5-8

Synchronization has attracted much attention in recent decades, because it can be applied to many fields, such as secure communications and laser dynamics.9 In the study of synchronization many useful methods have been proposed. The drive-response method,11,12 as a basic synchronization argument, was proposed by Pecora and Carroll, and is therefore also called the PC method. Generally, chaos control and chaos synchronization are different dynamics topics,13 but there are close relations between them.14 For example, one designs many useful different controllers to realize identical synchronization (IS) between two chaotic systems.6,15,16 Feedback control is widely used in engineering,17 and feedback synchronization is also widely studied.4,6

Feedback synchronization of general systems is a very important dynamical behavior, and it is realized to be related to the Lyapunov exponent of the uncontrolled system.18,19 The general form of this kind of system is as follows:

$$\dot{x} = f(x)$$

which can be regarded as the drive system for synchronization dynamics. The response system can be written as

$$\dot{y} = f(y) + k(x,t)(x - y),$$

where $k(x,t)$ is a function matrix describing the coupling strength, and $x, y \in \mathbb{R}^n$; $k(x,t)$ can be chosen as the forms used in Refs.4,20, and these feedback forms can induce different effects. Here we focus on the most simple form, that is, $k(x,t) = k = \text{diag}(k_1, k_2, \cdots, k_n)$.

In Refs.18,19, the authors investigated the uniform diagonal coupling mechanism $k = dI$, that is, $k_1 = k_2 = \cdots = k_n = d$. They demonstrated theoretically that the relation between the leading Lyapunov exponent (LLE), $\lambda_{\text{max}}$, and the smallest coupling strength $K_c$ for the synchronizing drive system to response system can be written as a simple form

$$\lambda_{\text{max}} = K_c.$$  

This equality reflects the connection between two inner quantities for system (1). It is noted that relation (3) can not only be used for understanding the essence of feedback control, which controls all the unstable trajectories to the stable state asymptotically, but also has been extended to estimate the LLE for complex systems by Stefanaki et al.,21,22 such as delay systems,23 which are not easy to be directly computed by traditional methods.

In this Letter, we use an adaptive synchronization mechanism24,25 to detect the complex behavior of the dynamical system. Firstly, in order to obtain a new quantity used here, we shall take the following steps.

Step 1: Construct the auxiliary drive-response system of Eq. (1),

$$\dot{x} = f(x), \quad \dot{y} = f(y) + k(t)(x - y),$$

$$k_i = m(x_i - y_i)^2, \quad i \in \Omega,$$

where $k(t) = \text{diag}(k_1(t), k_2(t), \cdots, k_n(t))$ and $m > 0$. The index set $\Omega$ is a subset of set $\{1, 2, \ldots, n\}$. If

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i Ω then we can consider k(t) ≡ 0. Since adaptive control is added, Ω is non-null. Here x(s) is generally selected as the most unstable variable. Note that gain terms for all variables are identical to m(x_s - y_s)^2, we conclude that k_i(t) = k_i, so Eq. (4) denotes 2n + 1-dimensional equations.

Adaptive feedback is a kind of feedback control. In fact, Eq. (4) is a special form of Eq. (2), since
\[ k_i(t) = m \int_0^t (x_i(u) - y_i(u))^2 du. \]

Step 2: Set initial values. Take k_i(0) = 0, i ∈ Ω and other initial values are arbitrary.

Step 3: Time evolution. When t → ∞, we have k_i(t) → k_i(∞), i ∈ Ω. Here there is a demonstration (similar to Ref. [25]). Assume that f(x) is continuous and satisfies the Lipschitz condition: there exists a positive constant M, such that |f_i(y) - f_i(x)| ≤ M||y - x||, i = 1, ..., n. For the reason that x(s) is the most unstable variable in all the system variables, we have |e_i| ≤ μ|e_i|, i = 1, ..., n, where μ is a positive number (of course, this inequality is not rigorous). Let e_s = y_s - x_s and L > μ/\sqrt{n}M. Construct the Lyapunov function V = \frac{1}{2}e_s^2 + \frac{1}{2m}(k_s - L)^2. Then we have \[ \dot{V} = e_s \cdot \dot{e}_s + (k_s - L)e_s^2 = [f_s(y) - f_s(x)]e_s - Le_s^2 \leq -M||e||e_s - Le_s^2 = (\mu/\sqrt{n}M - L)e_s^2 < 0. \] Thus we can conclude that V(t) < V(0), showing that V(t) is bounded, further, k_s(t) is bounded. Note that k_s ≥ 0, when t → ∞, we have k_s(t) → k_s(∞), since k_s = k, i ∈ Ω.

Of course, for each i ∈ Ω, k_i(∞) is related to the initial value and m, so we rewrite this limit values as k_i(∞)|\{x(0), y(0), k(0), m\}. Note that k_i(∞) > 0, for given initial values, k_i(∞)|\{m\} there must exist a lower limit as m → 0. If we denote this lower limit by K, we obtain
\[ K = \lim_{m \to 0} \inf_k k_i(\infty). \] (5)

For convenience, we call this the adaptive constant.

In what follows, we apply this notion to the unified chaotic system. According to Ref. [3], the unified chaotic system can be written as
\[ \begin{align*}
\dot{x} &= (25\alpha + 10)(y - x), \\
\dot{y} &= (28 - 35\alpha)x - xz + (29\alpha - 1)y, \\
\dot{z} &= xy - \frac{1}{3}(8 + \alpha)z.
\end{align*} \] (6)

This system connects the Lorenz system (\alpha = 0) with the Chen system (\alpha = 1), and the Lü system (\alpha = 0.8) is also a special case. When 0 ≤ \alpha ≤ 1, the unified systems are all in a chaotic state.\[26\]

Case 1: complete feedback control. Next, we present the unified system with complete feedback control as follows:
\[ \begin{align*}
\dot{x}_1 &= (25\alpha + 10)(y_1 - x_1) + k(x - x_1), \\
\dot{y}_1 &= (28 - 35\alpha)x_1 - x_1z_1 + (29\alpha - 1)y_1 + k(y - y_1), \\
\dot{z}_1 &= x_1y_1 - \frac{1}{3}(8 + \alpha)z_1 + k(z - z_1).
\end{align*} \] (7)

According to the above steps, we can obtain the corresponding adaptive constant. In order to construct the auxiliary system, we select s = 2, \Omega = \{1, 2, 3\}, that is, it has the same gain but different feedback controls of Eq. (7),
\[ \begin{align*}
x_1 &= (25\alpha + 10)(y_1 - x_1) + k(t)(x - x_1), \\
y_1 &= (28 - 35\alpha)x_1 - x_1z_1 + (29\alpha - 1)y_1 + k(t)(y - y_1), \\
z_1 &= x_1y_1 - \frac{1}{3}(8 + \alpha)z_1 + k(t)(z - z_1) \\
k &= m(y - y_1)^2, \tag{8}
\end{align*} \]
where m > 0 is constant.

We can obtain the adaptive constant by the above systems (7) and (8), according to the definition K_1 = \lim_{m \to 0} \inf k(\infty)|\{m\}.

To let m rapidly converge to zero, we select m as the power law form of cycling times l: m = m_0l^{-\beta}, m_0 = 5 \times 10^{-3}. Figure 1 shows much useful information. With m decaying to zero, k(\infty) oscillates around some value with a very small amplitude. Thus we can find that K_1 exists. Changing different initial values and selecting (3, 3, 3, 1, 1, 1) and (2, 1, 1, 3, 3, 3) as (x(0), y(0), z(0), x_1(0), y_1(0), z_1(0)), we make the simulations twice. The simulation result shows that K_1 is robust to the initial value. These features are difficult to find; furthermore, they are also difficult to be proved in theory.

![Fig. 1. (Color online) A semi-log plot of k(\infty) of Eq. (8) versus parameter m, m = 5 \times 10^{-3}, m = 5 \times 10^{-4}l^{-\beta}, l = 1, \ldots, 10. The two lines stand for the initial values (3, 3, 3, 1, 1, 1) (blue) and (2, 1, 1, 3, 3, 3) (red), respectively.](image-url)
Case 2: one-sided feedback control. In theory, we can add controls to the first or second equation in system (4). However, in practice, in order to make the controller simpler,[27] we would rather choose some most unstable variables[6] to add feedback control (e.g., one-sided feedback control), which is often effective in applications.

One-sided feedback control is generally achieved by adding the feedback control to the most unstable variable of the system under consideration. In this case, we can find some interesting phenomena and results. For a unified chaotic system, its one-sided feedback control form can be written as

\[
\begin{align*}
\dot{x}_1 &= (25\alpha + 10)(y_1 - x_1), \\
\dot{y}_1 &= (28 - 35\alpha)x_1 - x_1z_1 + (29\alpha - 1)y_1 + k(t)(y - y_1), \\
\dot{z}_1 &= x_1y_1 - \frac{1}{3}(8 + \alpha)z_1.
\end{align*}
\]  

For this kind of feedback control, we obtain the smallest coupling strength \(K_c\) by two methods here. The first method is to compute LLE of the response system. According to Ref. [6], \(K_c\) is just the value of \(k\) satisfying that the LLE of response system (9) is equal to zero, that is, \(K_c\) can be obtained by solving the equation \(\lambda_{\text{max}}(k) = 0\), where \(\lambda_{\text{max}}(k)\) is the LLE of Eq. (9) with the coupling strength \(k\). Using a traditional method (such as the Wolf method[28]) to compute the LLE of the response system with feedback control, the smallest coupling strength can be obtained.[6] When \(\alpha = 0\), \(K_c = 2.44\); when \(\alpha = 0.8\), \(K_c = 4.08\); when \(\alpha = 1\), \(K_c = 3.94\).

The second method is through simulation. This method needs a good synchronization criterion. For example, we often use the average synchronization error \(\langle \sigma \rangle = (1/T)\sum_{t=1}^{T} |e(t)|\), where, \(e(t) = (x_1(t) - x(t), y_1(t) - y(t), z_1(t) - z(t))\) after truncating a sufficient large scale time. However, the synchronization behavior of Eq. (6) is complex, and parameter \(\alpha\) impacts on synchronization. As shown in detailed simulations, we can see that intermittent behavior in the vicinity of the synchronization threshold is more obvious as \(\alpha\) becomes smaller from 1 to 0, demanding a larger time span to judge synchronization. Using this method, we can also obtain a series of \(K_c\) values (see in Table 1).

Similar to the former work, if system (6) is regarded as an objective system, the auxiliary system can be modeled as follows:

\[
\begin{align*}
\dot{x}_1 &= (25\alpha + 10)(y_1 - x_1), \\
\dot{y}_1 &= (28 - 35\alpha)x_1 - x_1z_1 + (29\alpha - 1)y_1 + k(t)(y - y_1), \\
\dot{z}_1 &= x_1y_1 - \frac{1}{3}(8 + \alpha)z_1 \\
\dot{k} &= m(y - y_1)^2,
\end{align*}
\]  

which shows that \(s = 2\), \(\Omega = [2]\). Through numerical stimulations, we also find that Eq. (10) can determine an adaptive constant \(K_2\), which is dependent on the system parameter \(\alpha\) but independent of initial values. For the three cases: \(\alpha = 0, 0.8, 1\), we obtain

\[K_2 = 2.74, 4.07, 4.04.\]

In Table 1, we compare the values of \(K_c\) by the LLE method and the simulation method to the values of \(K_2\) for \(\alpha = 0, 0.8, 1\).

Table 1. For the one-sided feedback case, the smallest coupling strength values \(K_c\) by computing LLE and stimulations and adaptive constants \(K_2\) for \(\alpha = 0, 0.8, 1\) are listed. This table shows that the adaptive constant can estimate \(K_c\), and is more effective than the LLE method.

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>0</th>
<th>0.8</th>
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</thead>
<tbody>
<tr>
<td>(K_c) from LLE method</td>
<td>2.44</td>
<td>4.08</td>
<td>3.94</td>
</tr>
<tr>
<td>(K_c) from simulation method</td>
<td>2.72</td>
<td>4.06</td>
<td>4.00</td>
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From Table 1, we can see that \(K_2\) is very near to the simulation value, that is,

\[K_2 = K_c.\]  

To further study \(K_2\), we examine the relation between \(K_2\) and \(\lambda_{\text{max}}\) of system (6). In simulations (see Fig.3), we set \((x_0, y_0, z_0, x_1(0), y_2(0), z_2(0)) = (1, 1, 3, 3, 3)\). Parameter \(\alpha\) varies in the interval \([0, 1]\). Firstly, we draw the plot \(K_2\) versus \(\alpha\). Next,

![Fig. 2.](image-url)  

**Fig. 2.** (Color online) The analysis plot of the unified chaotic system with parameter \(\alpha\) in the interval \([0, 1]\) shows that the adaptive constant \(K_1\) (blue dots) is identical to LLE \(\lambda_{\text{max}}\) (green dots) for each \(\alpha\). The initial values are \((x(0), y(0), z(0), x_1(0), y_1(0), z_1(0)) = (3, 3, 3, 1, 1, 1)\).

![Fig. 3.](image-url)  

**Fig. 3.** (Color online) An analysis plot of the unified chaotic system with parameter \(\alpha\) in the interval \([0, 1]\). There are three lines in the plot: \(\lambda_{\text{max}}\) versus \(\alpha\) (red), \(K_2\) versus \(\alpha\) (blue), and two times \(\lambda_{\text{max}}\) versus \(\alpha\) (green).

060505-3
besides the above-mentioned ones, the master threshold \( \kappa > \lambda_{\text{max}} \) can be estimated by using other methods. The smallest coupling strength \( \kappa \) cannot be realized in practice even if \( k > \lambda_{\text{max}} \). In other words, \( \kappa > \lambda_{\text{max}} \), according to Eq. (11) and we cannot give a precise estimation of the LLE in the case of one-sided coupled oscillators (9), which is quite different from the case with complete feedback. Although the precise estimation of the LLE cannot be realized in practice by this way, the smallest coupling strength (i.e., synchronization threshold) can be estimated by using other methods besides the above-mentioned ones, e.g., the master stability function [130].

From Fig. 3, we also find that larger \( \lambda_{\text{max}} \) cannot lead to larger \( K_2 \) or \( K_c \). For example, although \( \lambda_{\text{max}} \) for \( \alpha = 0.8 \) is greater than that for \( \alpha = 0.7 \), we have \( K_2 \) for \( \alpha = 0.8 \) being smaller than that for \( \alpha = 0.7 \). As a kind of feedback control, its strength should be positive correlation to the LLE of the drive system (6), but it is not the case, which is a surprising phenomenon.

In summary, we have proposed a new quantity \( K \), called the adaptive constant, which is generated by system (4), but determined by the uncontrolled system (1) in essence. \( K \) is related to chaotic behavior, so it can be regarded as a characteristic quantity.

An important chaotic system, the unified chaotic system, has been investigated. We examine the unified system with two kinds of feedback control forms, complete feedback control and one-sided feedback control. In simulations, for the former, we find that the adaptive constant is equal to the LLE of the unified system. By this result, we actually propose a new method to estimate the LLE rapidly. It should be emphasized that the unified chaotic system includes many chaotic systems with parameter \( \alpha \in [0, 1] \), which makes our results from simulations possess a rather general meaning, and may be applied to other dynamical systems. For the latter kind, the obtained results (see Table 1) represent our unexpected results: both adaptive constant and the smallest coupling strength are equal to each other.

From the above, we can obtain a unified conclusion that \( K = K_c \) holds for a unified chaotic system (at the moment without rigorous proof, though). Thus we propose a new method to estimate the smallest coupling strength and LLE. The new method is not only effective but also easy to use, and can be regarded as complementary to the simulation method.

References

**GENERAL**

<table>
<thead>
<tr>
<th>Article Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>060201</td>
<td>Numerical Solution of the Three-Dimensional Helmholtz Equation</td>
<td>Syed Tauseef Mohyud-Din, Ahmet Yıldırım</td>
</tr>
<tr>
<td>060301</td>
<td>A Controlled Phase Gate with Nitrogen-Vacancy Centers in Nanocrystal Coupled to a Silica Microsphere Cavity</td>
<td>XUE Peng</td>
</tr>
<tr>
<td>060302</td>
<td>Late-Time Evolution of the Phantom Scalar Perturbation in the Background of a Spherically Symmetric Static Black Hole</td>
<td>PAN Qi-Yuan, JING Ji-Liang</td>
</tr>
<tr>
<td>060303</td>
<td>Cryptanalysis and Improvement of a Quantum Secret Sharing Protocol between Multiparty and Multiparty with Single Photons and Unitary Transformations</td>
<td>ZHU Zhen-Chao, ZHANG Yu-Qing</td>
</tr>
<tr>
<td>060501</td>
<td>Network Traffic Anomaly Detection Method Based on a Feature of Catastrophe Theory</td>
<td>YANG Yue, HU Han-Ping, XIONG Wei, CHEN Jiang-Hang</td>
</tr>
<tr>
<td>060502</td>
<td>Discrete Capability of the Lempel–Ziv Complexity Algorithm on a Vibration Sequence</td>
<td>LI Jian-Kang, SONG Xiang-Rong, YIN Ke</td>
</tr>
<tr>
<td>060503</td>
<td>Spiking Behavior in Chua’s Circuit</td>
<td>JI Ying, BI Qin-Sheng</td>
</tr>
<tr>
<td>060504</td>
<td>Effect of Correlated Noises in a Genetic Model</td>
<td>ZHANG Li, CAO Li</td>
</tr>
<tr>
<td>060505</td>
<td>Investigation of a Unified Chaotic System and Its Synchronization by Simulations</td>
<td>WU Qing-Chu, FU Xin-Chu, Michael Small</td>
</tr>
</tbody>
</table>

**THE PHYSICS OF ELEMENTARY PARTICLES AND FIELDS**

<table>
<thead>
<tr>
<th>Article Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>061101</td>
<td>Exact Bosonic Solutions of the Truncated Skyrme Model</td>
<td>SHI Chang-Guang, HIRAYAMA Minoru</td>
</tr>
<tr>
<td>061201</td>
<td>Light Flavor Vector and Pseudo Vector Mesons from a Light-Cone QCD Inspired Effective Hamiltonian Model with SU(3) Flavor Mixing Interactions</td>
<td>GUO Xiao-Bo, TAO Jun, LI Lei, WANG Shun-Jin</td>
</tr>
<tr>
<td>061301</td>
<td>Ideal Mixing of Scalar Mesons and Hyperon-Nucleon Interaction</td>
<td>DAI Lian-Rong</td>
</tr>
<tr>
<td>061302</td>
<td>Experimental Prospects of the Bc Studies of the LHCb Experiment</td>
<td>GAO Yuan-Ning, HE Ji-Bo, Patrick Robbe, Marie-Hélène Schune, YANG Zhen-Wei</td>
</tr>
</tbody>
</table>

**NUCLEAR PHYSICS**

<table>
<thead>
<tr>
<th>Article Number</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>062101</td>
<td>Description of the Triaxial Strongly Deformed Bands in $^{160,161}$Tm and $^{163}$Tm</td>
<td>ZHANG Da-Li, DING Bin-Gang</td>
</tr>
<tr>
<td>062102</td>
<td>Relativistic Mean Field Study of the $Z = 117$ Isotopic Chain</td>
<td>GAO Yuan, ZHANG Hong-Fei, LI Jun-Qing, CHEN Xi-Meng, GUO Wen-Jun</td>
</tr>
<tr>
<td>062103</td>
<td>Improvement of a Fission-Like Model for Nuclear $\alpha$ Decay</td>
<td>WANG Yong-Jia, ZHANG Hong-Fei, ZUO Wei, LI Jun-Qing</td>
</tr>
<tr>
<td>062104</td>
<td>Properties of the $\beta$-Delayed Proton Decay of $^{147}$Er</td>
<td>MA Fei, ZHOU Xiao-Hong, ZHENG Yong, XU Shu-Wei, XIE Yuan-Xiang, CHEN Liang, ZHANG Yu-Hu, LI Zhan-Kui, QIANG Yun-Hua, LEI Xiang-Guo, GUO Ying-Xiang, GUO Song, DING Bing, WANG Hai-Xia, LI Guang-Shun, ZHOU Hou-Bing</td>
</tr>
</tbody>
</table>

(Continued on inside back cover)
062501 Collective Band Structures and Identification of One-Phonon and Two-Phonon $\gamma$-Vibrational Bands in $^{109}$Tc

062502 Nuclear Hexadecapole Deformation Effects on the Production of Super-Heavy Elements
WANG Nan, DOU Liang, ZHAO En-Guang, Werner Scheid

062503 Finding a Probe for Extracting Information on the Momentum Dependent-Interaction in Heavy Ion Collisions
LIU Jian-Ye, GUO Wen-Jun

062504 Systematic Study on System Size Dependence of Global Stopping: Role of Momentum-Dependent Interactions and Symmetry Energy
Sanjeev Kumar, Suneel Kumar

ATOMIC AND MOLECULAR PHYSICS

063101 Precision Calculations of Atomic Polarizabilities: A Relevant Physical Quantity in Modern Atomic Frequency Standard
GAO Xiang, LI Jia-Ming

063201 Kinetic Energy of Trapped Ions Cooled by Buffer Gas
CHEN Liang, SHE Lei, LI Jiao-Mei, GAO Ke-Lin

063202 Influence of Laser Wavelength on Laser-induced Breakdown Spectroscopy Applied to Semi-Quantitative Analysis of Trace-Elements in a Plant Sample
ZHANG Da-Cheng, MA Xin-Wen, WEN Wei-Qiang, ZHANG Peng-Ju, ZHU Xiao-Long, LI Bin, LIU Hui-Ping

063301 Effects of Bounding Potential on High-Order Harmonic Generation with $\text{H}_2^+$
ZHAO Jing, ZHAO Zeng-Xiu

FUNDAMENTAL AREAS OF PHENOMENOLOGY(INCLUDING APPLICATIONS)

064101 Transmission Properties of One-Dimensional Photonic Crystals Containing Anisotropic Metamaterials
ZHANG Li-Wei, YAN Ling-Ling, ZHAO Yu-Huan, LIU Li

064201 A Zone Plate as a Tunable Terahertz Filter
FENG Hui, WANG Li

064202 Threshold Analysis of a THz-Wave Parametric Oscillator
LI Zhong-Yang, YAO Jian-Quan, ZHU Neng-Nian, WANG Yu-Ye, XU De-Gang

064203 New Expressions for Dark-Hollow Light Beams
LI Jian-Long

064204 Optical Properties of Plasmon Resonances with Ag/SiO$_2$/Ag Multi-Layer Composite Nanoparticles
MA Ye-Wan, ZHANG Li-Hua, WU Zhao-Wang, ZHANG Jie

064301 Broadband Source Ranging in Shallow Water Using the $\Omega$-Interference Spectrum
ZHAO Zhen-Dong, WANG Ning, GAO Da-Zhi, WANG Hao-Zhong

064302 Asymmetric Oscillation and Acoustic Response from an Encapsulated Microbubble Bound within a Small Vessel
HUANG Bei, ZHENG Hai-Rong, ZHANG Dong

064303 Bonding Interface Imaging and Shear Strength Prediction by Ultrasound
LI Yong-An, MAO Jie, WANG Xiao-Min, AN Zhi-Wu, ZHUANG Qiao, LI Ming-Xuan

064401 Temperature-Dependent Viscosity Effects on Non-Darcy Hydrodynamic Free Convection Heat Transfer from a Vertical Wedge in Porous Media
A. M. Salem

064601 Flutter of Finite-Span Flexible Plates in Uniform Flow
BAO Chun-Yu, TANG Chao, YIN Xie-Zhen, LU Xi-Yun

064701 Turbulence Modulations in the Boundary Layer of a Horizontal Particle-Laden Channel Flow
LI Jing, LIU Zhao-Hui, WANG Han-Feng, CHEN Sheng, LIU Ya-Ming, HAN Hai-Feng, ZHENG Chu-Guang
PHYSICS OF GASES, PLASMAS, AND ELECTRIC DISCHARGES

065201 Transition of Discharge Mode of a Local Hollow Cathode Discharge
LI Shang, OUYANG Ji-Ting, HE Feng

065202 First Observation of Neoclassical Tearing Modes in the HL-2A Tokamak
JI Xiao-Quan, YANG Qing-Wei, LIU Yi, ZHOU Jun, FENG Bei-Bin, YUAN Bao-Shan

CONDENSED MATTER: STRUCTURE, MECHANICAL AND THERMAL PROPERTIES

066101 Structural Investigation of Solid Methane at High Pressure
ZHAO Juan, FENG Wan-Xiang, LIU Zhi-Ming, MA Yan-Ming, HE Zhi, CUI Tian, ZOU Guang-Tian

066201 Dynamic Tensile Behavior and Fracture Mechanism of Polymer Composites Embedded with Tetraneedle-Shaped ZnO Nanowhiskers
RONG Ji-Li, WANG Xi, CAO Mao-Sheng, WANG Da-Wei, ZHOU Wei, Xu Tian-Fu

066801 Fabrication of Anodic Aluminum Oxide Templates with Small Interpore Distances
WANG Na, ZHANG Wen-Di, XU Ji-Peng, MA Bin, ZHANG Zong-Zhi, JIN Qing-Yuan, E. Bunte, J. Hüpkes, H. P. Bochem

066802 Molecular-Dynamics Simulations of Droplets on a Solid Surface
GAO Yu-Feng, SUN De-Yan

066803 Edge Effects on Growth of Ordered Stress Relief Patterns in Free Sustained Aluminum Films
YU Sen-Jiang, ZHANG Yong-Ju, CHEN Miao-Gen

CONDENSED MATTER: ELECTRONIC STRUCTURE, ELECTRICAL, MAGNETIC, AND OPTICAL PROPERTIES

067201 Improved Programming Efficiency through Additional Boron Implantation at the Active Area Edge in 90 nm Localized Charge-Trapping Non-volatile Memory
XU Yue, YAN Feng, CHEN Dun-Jun, SHI Yi, WANG Yong-Gang, LI Zhi-Guo, YANG Fan, WANG Jie-Hua, LIN Peter, CHANG Jian-Guang

067202 Spin Transport in a Magnetic Superlattice with Broken Two-Fold Symmetry
HUO Qiu-Hong, WANG Ru-Zhi, CHEN Si-Ying, XUE Kun, YAN Hui

067203 Van der Pauw Hall Measurement on Intended Doped ZnO Films for p-Type Conductivity
GUO Yang, LIU Yao-Ping, LI Jun-Qiang, ZHANG Sheng-Li, MEI Zeng-Xia, DU Xiao-Long

067204 Capacitance of Organic Schottky Diodes Based on Copper Phthalocyanine (CuPc)
LI Zhong-Liang, WU Zhao-Xin, JIAO Bo, MAO Gui-Lin, HOU Xun

067301 A High Performance Silicon-on-insulator LDMOST Using Linearly Increasing Thickness Techniques
GUO Yu-Feng, WANG Zhi-Gong, SHEU Gene, CHENG Jian-Bing

067302 Measurement of GaN/Ge(001) Heterojunction Valence Band Offset by X-Ray Photoelectron Spectroscopy
GUO Yan, LIU Xiang-Lin, SONG Hua-Ping, YANG An-Li, ZHENG Gao-Lin, WEI Hong-Yuan, YANG Shao-Yan, ZHU Qin-Sheng, WANG Zhan-Guo

067303 Self-Consistent Study of Conjugated Aromatic Molecular Transistors
WANG Jing, LIANG Yun-Ye, CHEN Hao, WANG Peng, R. Note, H. Mizuseki, Y. Kawazoe

067304 Noncommutative Chern–Simons Description of the Fractional Quantum Hall Edge
HUANG Wei, WANG Hao-Long, YAN Mu-Lin

067305 Spin-charge Separation of the Luttinger Model after an Interaction Quench
ZHOU Zong-Li, ZHANG Guo-Shun, LUO Rui

067306 Shot Noise in Aharonov–Casher Rings
LIN Liang-Zhong, ZHU Rui, DENG Wen-Ji

067501 Synthesis and Characteristics of Electrodeposited Co35-Mg75 Nanorods
LIU Li-Hu, GU Jian-Jun, Li Hai-Tao, CAI Ning, SUN Hui-Yan

067502 Soft Magnetism and High Frequency Properties of Fe60Co35-Mg82 Granular Thin Films
YAO Dong-Sheng, GE Shi-Hui, ZHOU Xue-Yun, ZHANG Bang-Ming, ZUO Hua-Ping
067503 Permanent Magnetic Properties of Melt-Spun YCo/Cr Ribbons
WANG Fei, YAN Yu, YUAN Zhou, BAI Xue, DU Xiao-Bo, WANG Wen-Quan, SU Feng, JIN Han-Min

067504 Elastic Modulus of Fe_{72.5}Ga_{27.5} Magnetostrictive Alloy
ZHOU Xiao-Xi, LIU Jing-Hua, JIANG Cheng-Bao

067801 Effect of Media on the Electric Field of a Rhombic Nanostructure Array
ZHOU Shao-Li, ZHOU Wei

068101 High Quality AlN with a Thin Interlayer Grown on a Sapphire Substrate by Plasma-Assisted Molecular Beam Epitaxy
REN Fan, HAO Zhi-Biao, ZHANG Chen, HU Jian-Nan, LOU Yi

068201 Fe Nanoparticle Production by an Atmospheric Cold Plasma Jet
ZHANG Yu-Tao, GUO Ying, WANG Da-Wang, FENG Yan, MA Teng-Cai

068501 Simulation of Voltage SET Operation in Phase-Change Random Access Memories with Heater Addition and Ring-Type Contactor for Low-Power Consumption by Finite Element Modeling
GONG Yue-Feng, SONG Zhi-Tang, LING Yun, LIU Yan, LI Yi-Jin

068701 Simulation of the Second Grade Fluid Model for Blood Flow through a Tapered Artery with a Stenosis
S. Nadeem, Noreen Sher Akbar

068901 Effect of Eliminating Edges on Robustness of Scale-Free Networks under Intentional Attack
LI Yong, WU Jun, ZOU An-Quan

069901 Addendum and Corrigendum: “Heavy Quarkonium Spectra in a Quark Potential Model”
CHEN Hong