TESTING FOR NON-LINEARITY IN ASEAN FINANCIAL MARKETS

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Abstract

With abounding evidence of non-linearity in financial markets of developed countries, this study attempts to narrow the gap in the literature of ASEAN countries, with a focus on the foreign exchange and stock markets. The outcomes of our econometric investigation using the Hinich bispectrum test provide strong support for the presence of non-linearity in all the ASEAN-5 exchange rates and stock returns series. Further application of the Lukkonen-Saikkonen-Teräsvirta (LST) test reinforces our conclusion that the financial time series data of ASEAN-5 exhibit non-linear dependencies. These findings, while highlighting the fact that researchers cannot take the linear assumption as granted, also point to the need to test for non-linearity as a preliminary diagnostic tool to determine the nature of the data generating process before any further empirical analysis. This study has strong implication on the empirical work of ASEAN-5 financial markets. Specifically, the results suggest the use of empirical methods that is more robust if the data generating process is non-linear.

Keywords: Non-linearity; Data generating process; Hinich bispectrum test; Lukkonen-Saikkonen-Teräsvirta (LST) test; ASEAN foreign exchange markets; ASEAN stock markets.

I. INTRODUCTION

It is an accepted fact that financial economics has been dominated over the past decade by linear paradigm, which assumes that economic time series conform to linear models or can be well approximated by a linear model. For example, empirical tests of market efficiency, purchasing power parity, tests of stationarity, cointegration, causality and many of the empirical models of asset pricing have implicitly assumed that the underlying dynamics are in linear form or can be made linear by a simple transformation.

However, there is ample empirical evidence against the linear paradigm. Theoretically, there is no reason to believe that economic systems must be intrinsically linear (see, for example, Pesaran and Potter, 1993; Campbell *et al.*, 1997; Barnett and Serletis, 2000). Empirically, there were a great number of studies showing that financial time series exhibit non-linear dependencies (see, for example, Hsieh, 1989, 1991; Scheinkman and LeBaron, 1989; De Grauwe *et al*., 1993; Abhyankar *et al.*, 1995; Steurer, 1995; Brooks, 1996; Barkoulas and

Travlos, 1998; Opong, *et al.*, 1999). With this development, the subject has now moved to a new direction. This new direction is, of course, the study of non-linearity. In the words of Campbell *et al.* (1997: 467), “A natural frontier for financial econometrics is the modelling of non-linear phenomenon”. The main driving force behind this shift is the developments in the mathematical and statistical analysis of dynamics systems, which are able to uncover a more complex form of dependencies in time series that would otherwise appear to be random. A good testimony of the growing interest in non-linear studies would be the founding of a specialized international journal entitled *Studies in Non-linear Dynamics and Econometrics*.

In the literature, there is no generally agreed definition for ‘non-linearity’. From the definition given by De Grauwe *et al.* (1993: 244), a system $X_t = h(\Omega_t, \alpha)$ is called a non-linear system if it is not possible to regenerate X_t by one linear model:

$$X_t = \sum_{i=0}^{\infty} \gamma_i \varepsilon_{t-i} \quad \text{and } \varepsilon \text{ is white noise and}$$

$$\sum_{i=0}^{\infty} \gamma_i \text{ is such that } \sum_{i=0}^{\infty} |\gamma_i| < \infty \qquad (1)$$

According to De Grauwe *et al.* (1993), the definition of non-linearity stems from the negation of linearity. This leaves a lot of other possibilities open for a so-called non-linear system. For example, Hsieh (1989) divided the realm of non-linear dependencies into three categories. Additive non-linearity, also known as non-linear-in-mean, enters a process through its mean or expected value, so that each element in the sequence can be expressed as the sum of zero-mean random element and a non-linear function of past elements[1]. With multiplicative non-linearity, or non-linear-in-variance, each element can be expressed as the product of a zero-mean random element and a non-linear function of past elements, so that the non-linearity affects the process through its variance[2]. The final category is known as hybrid dependence, in which non-linearity enters through both the mean and the variance[3].

Testing for non-linearity has become extremely popular in the financial econometrics literature in recent years, though the focus is on financial markets of developed countries. In principle, testing for non-linearity can be viewed as general test of model adequacy for linear

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[1] The non-linear moving average model, the threshold autoregressive model and the bilinear model are examples of additive dependence.
[2] The ARCH-type models are examples of multiplicative dependence.
[3] The ARCH-in-the-mean and GARCH-in-the-mean are examples of hybrid dependence.

models (Hinich and Patterson, 1989) and it has been argued that if the underlying generating process for a time series is non-linear in nature, then it would be inappropriate to employ linear methods. For instance, most of the widely applied statistical tests like the unit root or stationary tests, the Granger causality test and the cointegration test are all build on the basis of linear autoregressive model. Taylor and Peel (1997) and Sarno (2000), amongst others, illustrated that the adoption of linear stationarity tests are inappropriate in detecting mean reversion if the true data generating process is in fact a stationary non-linear process. On the other hand, the Monte Carlo simulation evidence in Bierens (1997) indicated that the standard linear cointegration framework presents a mis-specification problem when the true nature of the adjustment process is non-linear and the speed of adjustment varies with the magnitude of the disequilibrium. Thus, if the underlying process of a time series is indeed non-linear in nature, one would have to resort to empirical methods like non-parametric cointegration test due to Bierens (1997), non-linear stationarity tests (Sarno, 2001; Chortareas *et al.*, 2002; Kapetanios *et al.*, 2003) and non-linear causality test (Baek and Brock, 1992). To sum, testing for non-linearity is gaining popularity among researchers as a preliminary diagnostic tool to determine the nature of the data generating process before any further empirical analysis.

Over the past few decades, numerous studies have documented the existence of non-linear dependencies in exchange rates returns series (see, for example, Hsieh, 1989; De Grauwe *et al*., 1993; Steurer, 1995; Brooks, 1996). The stock markets have also attracted the attention of researchers with substantial evidence supporting the presence of non-linearity in stock returns series (see, for example, Scheinkman and LeBaron, 1989; Hsieh, 1991; Abhyankar *et al.*, 1995, 1997; Barkoulas and Travlos, 1998; Opong, *et al.*, 1999). However, much of this evidence has been drawn from the widely traded financial markets of well-developed countries. Though more efforts are now being directed towards the ASEAN foreign exchange markets and stock markets in light of their increasing importance to the investment world and the world economy, to the knowledge of the writers, most of the earlier empirical studies on ASEAN financial markets have taken the linear assumption as granted. In views of the profound implication that testing for non-linearity has on model adequacy, this study attempts to bridge the gap in the literature by addressing the issue of whether the ASEAN financial markets are governed by non-linear dynamics.

This paper is organized as follows: Section II provides a brief review on the methodology commonly used in non-linear literature. This is followed by a description on the methodology. Section IV presents the empirical results as well as the analysis of the findings. Finally, concluding remarks are given at the end of the paper.

II. A REVIEW ON METHODOLOGY

Most of the empirical studies in the literature have extensively applied the Brock-Dechert-Scheinkman test (henceforth refer to BDS test) in testing for non-linearity in financial time series data [4] (see, for example, Scheinkman and LeBaron, 1989; Hsieh, 1989, 1991; De Grauwe *et al.*, 1993; Steurer, 1995; Abhyankar *et al*., 1995, 1997; Brooks, 1996; Barkoulas and Travlos, 1998; Opong *et al.*, 1999; Mahajan and Wagner, 1999). However, the BDS (Brock, *et al.*, 1996) test does not provide a direct test for non-linearity because the sampling distribution of the BDS test statistic is not known, either in finite samples or asymptotically, under the null hypothesis of non-linearity. The rejection of the null of independent and identical distribution (i.i.d.) in the BDS test can be due to non-white linear and non-white non-linear dependence in the data. Thus, the effects of linear serial dependencies have to be filtered out by fitting the best possible linear model before the BDS test can be applied to detect any non-linear departure from the i.i.d. null. However, there is always the concern that the rejection of the null by the BDS test could be due to the possibility of imperfect pre-whitening. This concern is well directed since much of the Monte Carlo research that has been published on the BDS test (see example, Brock *et al.*, 1991) has emphasized the pre-testing issue and the potential dependence of the properties of the test on the prior linear filter. Some of the test's sensitivity to non-linearity could be a result of remaining linear dynamics in the data.

Another popular non-linear test is the Hinich bispectrum test (Hinich, 1982), which involves estimating the bispectrum of the observed time series (see, for example, De Grauwe *et al.*, 1993; Abhyankar *et al.*, 1995; Brooks, 1996; Vilasuso and Cunningham, 1996). Unlike the BDS test, the Hinich bispectrum test provides a direct test for a non-linear generating mechanism, irrespective of any linear serial dependencies that might be present. Thus, pre-whitening is not necessary in using the Hinich approach. Even if pre-whitening is done anyway, the adequacy of the pre-whitening is irrelevant to the validity of the test. Ashley *et al.* (1986) presented an equivalence theorem to prove that the Hinich linearity test statistic is invariant to linear filtering of the data, even if the filter is estimated. Thus, the linearity test can be applied to the original returns series, or to the residuals of a linear model with no loss of power.

[4] The growing popularity of the BDS test has witnessed its incorporation into commercial statistical package of E-Views version 4.0.

While the rejection of the null of linearity in the Hinich bispectrum test provides a strong support for the presence of non-linearity (Barnett *et al.*, 1997), the evidence gives researchers little clue as to what the appropriate functional form for the resultant non-linear model should be. This is basically due to its portmanteau or general nature, that is it does not have a specific alternative hypothesis. Lukkonen *et al.* (1988) developed a linearity test (henceforth refer to LST test) to test for the null of no non-linearity against the alternative of Smooth Transition Autoregressive (STAR) type non-linearity. Sarantis (1999), Taylor and Peel (2000), Sarno (2000), Baum *et al.* (2001), amongst others, have demonstrated the usefulness of LST test in detecting non-linear behaviour of exchange rates series.

III. METHODOLOGY

The Data

The Association of Southeast Asian Nations (ASEAN) comprises Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand and Vietnam. However, this study focuses only on Indonesia, Malaysia, the Philippines, Singapore, and Thailand (hereafter denotes as ASEAN-5). One main consideration is data availability of the selected member countries.

The daily spot exchange rates for ASEAN-5 currencies (expressed as the price of a country's currency in terms of the U.S. dollar) are employed in this study, with different sample period due to data availability. The daily data of Singaporean dollar (SGD/USD) and Thai baht (THB/USD) spans from January 2, 1990 to December 31, 2002. However, the sample period for Malaysian ringgit (MYR/USD) is up to 31 August 1998. The period after this is excluded from the current study because Malaysia adopted a fixed ringgit regime from September 1, 1998. At the time of writing, the Malaysian ringgit peg at 3.80 to the U.S. dollar has held firm. As for Indonesian rupiah (IDR/USD) and the Philippines peso (PHP/USD), the sample period covers November 16, 1995 to December 31, 2002.

The daily data of Singaporean dollar (SGD/USD), Malaysian ringgit (MYR/USD) and Thai baht (THB/USD) used in this study are drawn from the Federal Reverse Statistical Release[5]. The source for the Indonesian rupiah (IDR/USD) and the Philippines peso (PHP/USD) daily rates comes from the Pacific Exchange Rate Service[6].

As for ASEAN-5 stock markets, the data consist of daily closing prices for all five ASEAN stock market indices: Jakarta Composite Index (JCI), Kuala Lumpur Composite Index (KLCI), Philippines Composite Price (PCOMP), Singapore Straits Times Index (STI) and Stock Exchange of Thai (SET). The data are collected from Kuala Lumpur Stock Exchange (KLSE) and cover the sample period from 2 January 1990 to 31 October 2001. All the indices are denominated in local currency units.

In this study, both the exchange rates and stock indices are transformed into a series of continuously compounded percentage returns (r_t), using the relationship:

$$r_t = 100^* \ln(P_t / P_{t-1}) \tag{2}$$

where P_t is the closing price (exchange rate or stock index) on day *t*, and P_{t-1} the price (exchange rate or stock index) on the previous trading day.

Hinich Bispectrum Test

Hinich (1982) laid out a statistical test for determining whether an observed stationary time series (y_t) is linear. It is possible that y_t is linear without being Gaussian[7], but all of the

[5] These daily data are obtained from the Federal Reserve Board's official website at http://www.federalreserve.gov/releases/H10/hist on 19/3/2003. The H.10 release contains daily rates of exchange of major currencies against the U.S. dollar.

[6] These daily data are obtained from the web location of Pacific Exchange Rate Service at http://pacific.commerce.ubc.ca/xr/data.html on 19/3/2003.

[7] When the distribution of { y_{n_1}, …, y_{n_N} } is multivariate normal for all n_1, …, n_N, then the series is called Gaussian.

stationary Gaussian time series are linear. The Hinich bispectrum test involves estimating the bispectrum of the observed time series, which is the double Fourier transform of the third-order cumulant function.

In this section, we present a brief description of the testing procedures presented by Hinich (1982). Let y_t denote a third order stationary time series, where the time unit, *t*, is an integer. The third-order cumulant function of y_t is defined to be $C_{yyy}(m,n) = E[y_{t+n} y_{t+m} y_t]$ for each (*m*, *n*) when E[y_t] = 0, in which $n \le m$ and $m = 0, 1, 2, \ldots$

Since third-order cumulants are difficult to interpret, and their estimates are even difficult to fathom, the double Fourier transform of the third-order cumulant function (called the bispectrum) is calculated.

The bispectrum at frequency pair (f_1, f_2) is the double Fourier transform of $C_{yyy}(m,n)$:

$$B_y(f_1, f_2) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} C_{yyy}(m,n) \exp[-i2\pi(f_1 m + f_2 n)] \quad (3)$$

assuming that $|C_{yyy}(m,n)|$ is summable. The symmetries of $C_{yyy}(m,n)$ translate into symmetries of $B_y(f_1, f_2)$ that yield a principal domain for the bispectrum, which is the triangular set $\Omega = \{0 < f_1 < 1/2,\ f_2 < f_1,\ 2f_1 + f_2 < 1\}$.

Since the spectrum of y_t is $S_y(f) = \sigma_u^2 |A(f)|^2$, it follows that:

$$\psi^2(f_1, f_2) \equiv \frac{|B_y(f_1, f_2)|^2}{S_y(f_1) S_y(f_2) S_y(f_1 + f_2)} = \frac{\mu_3^2}{\sigma_u^6} \quad (4)$$

for all f_1 and f_2 in Ω, where $A(f) = \sum_{n=0}^{\infty} a(n) \exp(-i2\pi f_n)$. The left hand side of Equation (4) defines the square of the skewness function of { y_t , $\psi(f_1, f_2)$ }. Linearity and Gaussianity of y_t are tested through the null hypotheses that $\psi(f_1, f_2)$ is constant over all frequencies and that $\psi(f_1, f_2)$ is zero over all frequencies respectively using the estimated bispectrum.

The test statistics for both hypotheses are reduced to:

$$\hat{S} = 2\sum_m \sum_n \left|\hat{y}_{m,n}\right|^2 \tag{5}$$

at the frequency pair (m, n) where:

$$\hat{y}_{m,n} = \frac{\hat{B}_y(m,n)}{[N/M^2]^{1/2}[\hat{S}_y(g_m)\hat{S}_y(g_n)\hat{S}_y(g_{m+n})]^{1/2}} \tag{6}$$

Under the null hypothesis of Gaussianity, $\hat{S}$ is distributed chi-squared with $2P$ degree of freedom, with P being the number of squares whose centres are in the principal domain. Hinich (1982) showed that, asymptotically, the transformation of $\hat{S}$ is well approximated by a normal distribution with zero mean and unit variance. Thus, the significance of the test statistics is readily determined from standard normal tables.

On the other hand, if y_t is linear but not Gaussian, the sample dispersion of $2\left|\hat{y}_{m,n}\right|^2$ should not differ significantly from the population dispersion of $\chi^2(2,\hat{\lambda})$, where $\hat{\lambda} = \{\hat{S}/P\} - 2$. Linearity test statistics examine whether the sample dispersion is significantly different from that of $\chi^2(2,\hat{\lambda})$. The distribution of the standard normal is used to produce a one-sided test, in which the null is rejected if the test statistic is greater than the critical value at the chosen level of significance.

It is important to note that this dispersion can be measured in many ways. We used the 90 percent quantile of the empirical distribution in order to get a more plausible result[8]. Another important consideration in the implementation of the bispectrum test is the parameter M, the frame size. The choice of M governs the trade-off between the bias and variance of the

[8] In a personal communication, Hinich recommended the use of the 90 percent quantile.

estimator. In this respect, the larger (smaller) the *M*, the smaller (larger) the finite sample variance and the larger (smaller) the sample bias. Owing to this trade-off, there is no unique value of *M* that is appropriate to use. In this study, we set *M* equal to 30[9].

Lukkonen-Saikkonen-Teräsvirta Test (LST Test)

This study also adopts the linearity test suggested in the work of Luukkonen *et al.* (1988) to test the adequacy of the linearity nature of the returns series for ASEAN-5 financial markets.

The LST test equation is given by:

$$y_t = a_0 + \sum_{i=1}^{p} a_i \; y_{t-i} + \sum_{i=1}^{p} (b_{1i} y_{t-i} y_{t-d} + b_{2i} y_{t-i} y_{t-d}^2 + b_{3i} y_{t-i} y_{t-d}^3) + \xi_t \qquad (7)$$

where y_t is the series of interest (in our case, returns series of ASEAN-5 financial market); ξ_t is white noise residuals with zero mean and constant variance under the null hypothesis.

The test procedure as specified in Equation 7 is the third order auxiliary regression in the work of Luukkonen *et al.* (1988)[10].

The null hypothesis to be tested (Equation 7) is that:

H_0: All *b*'s = 0 (implying y_t follows a linear process) (8)

against the alternative that at least one *b* is non-zero, which implies that y_t follows a STAR-type non-linear process[11].

[9] Hinich recommended a frame size of 30 for our sample sizes in order to improve the power of the test.
[10] See Luukkonen *et al.* (1988) for other versions of auxiliary regressions.
[11] Teräsvirta (1994) and van Dijk *et al.* (2001) provide details on STAR model.

This null hypothesis may be tested using LST statistic based on the following estimation procedure:

(i) Regress y_t on {1, y_{t-i}; i = 1, …, p}. Obtain the estimated residuals $\hat{\xi}_t$ and compute the residual sum of squares, $SSR_L = \sum_{t=1}^{T} \hat{\xi}_t^2$

(ii) Regress $\hat{\xi}_t$ on {1, y_{t-i}, $y_{t-i}y_{t-d}$, $y_{t-i}y_{t-d}^2$, $y_{t-i}y_{t-d}^3$ }. Obtain the resulted residuals $\hat{\omega}_t$ and compute the residual sum of squares $SSR_N = \sum_{t=1}^{T} \hat{\omega}_t^2$

(iii) Compute the test statistic

$$LST = \frac{T(SSR_L - SSR_N)}{SSR_L} \quad (9)$$

where *T* is the sample size. LST has an asymptotic χ^2 distribution with 3*p* degrees of freedom (Luukkonen *et al.*, 1988). If the computed LST statistic is large enough, one has sufficient evidence to reject the linear null thereby implying y_t follows a non-linear dynamics.

Note that the optimal lag length, *p* and the delay parameter, *d* have to be determined in advance. Following Taylor and Peel (2000), this study fixes the optimal *p* as suggested by partial autocorrelation functions (PACF). The linearity test is performed for a class of *d* that ranges from 1 to 12. The optimal *d* is chosen from the one that minimizes the *p*-value of the LST test statistic.

IV. EMPIRICAL RESULTS

Before proceed to the formal testing of non-linearity, we conduct the preliminary analysis on the ASEAN-5 exchange rates and stock returns series in order to get a better view of some of the important statistical features.

Table 1 provides summary statistics for all the ASEAN-5 exchange rates returns series. The means are quite small. The range of daily changes, however, is relative high. Moving beyond the basic mean and standard deviation measurements to higher-order moments, the skewness statistics show that all the returns series are asymmetry. The MYR, SGD and PHP exhibit some degree of negative or left-skewness while THB and IDR are right-skewed. On the other hand, the distributions of returns for all the series are highly leptokurtic, in which the tails of its distribution taper down to zero more gradually than do the tails of a normal distribution. Not surprisingly, given the non-zero skewness levels and excess kurtosis demonstrated within these series of returns, the Jarque-Bera (JB) test strongly rejects the null of normality for all the ASEAN-5 exchange rates returns series. These results conform to the consensus in the literature that the distributions of exchange rates returns series are non-normal (see, for example, Hsieh, 1988; Steurer, 1995; Brooks, 1996). Similar statistical properties are found in the stock returns series of ASEAN-5, which is provided in Table 2.

Table 1
Summary Statistics for ASEAN-5 Exchange Rates Returns Series

	IDR	**MYR**	**PHP**	**SGD**	**THB**
Sample Period	16/11/1995 31/12/2002	2/1/1990 31/8/2001	16/11/1995 31/12/2002	2/1/1990 31/12/2002	2/1/1990 31/12/2002
No. of observations	1759	2179	1773	3267	3210
Mean	0.078	0.020	0.040	-0.003	0.016
Median	0.017	0.000	0.008	0.000	0.000
Maximum	30.189	7.196	7.176	2.762	20.769
Minimum	– 23.316	– 9.157	– 12.518	– 4.144	– 6.353
Std deviation	2.512	0.695	0.776	0.356	0.753
Skewness	1.172	– 0.084	– 1.304	– 0.908	6.185
Kurtosis	34.783	43.141	54.518	20.905	196.243
JB normality test statistic *p*-value	7.444×10^4 (0.000)*	1.463×10^5 (0.000)*	1.966×10^5 (0.000)*	4.409×10^4 (0.000)*	5.015×10^6 (0.000)*

Note: * denotes extremely small *p*-value.

Table 2
Summary Statistics for ASEAN-5 Stock Returns Series

	JCI	KLCI	PCOMP	STI	SET
Sample Period	2/1/1990 31/10/2001	2/1/1990 31/10/2001	2/1/1990 31/10/2001	2/1/1990 31/10/2001	2/1/1990 31/10/2001
No. of observations	3087	3087	3087	3087	3087
Mean	– 0.001	0.002	– 0.003	0.005	– 0.038
Median	0.000	0.000	0.000	0.000	0.000
Maximum	13.128	20.817	16.178	14.868	11.350
Minimum	– 12.732	– 24.153	– 9.744	– 9.672	– 10.028
Std deviation	1.558	1.7153	1.6653	1.358	1.889
Skewness	0.485	0.461	0.5571	0.201	0.287
Kurtosis	14.195	36.898	11.558	14.070	7.432
JB normality test statistic (*p*-value)	1.624×10^4 (0.000)*	1.479×10^5 (0.000)*	9.580×10^3 (0.000)*	1.578×10^4 (0.000)*	2.569×10^3 (0.000)*

Note: * denotes extremely small *p*-value.

Hinich Bispectrum Test

Subsequently, the Hinich bispectrum test is applied on the ASEAN-5 exchange rates and stock returns series. The second column of Table 3 and Table 4 respectively report the results of the bispectrum Gaussianity test on both sets of financial time series data. It is obvious that the null is strongly rejected in each of the return series, which confirms the non-normality of the returns series suggested by Jarque-Bera normality test obtained earlier in Table 1 and Table 2.

Table 3
Bispectrum Test Results for ASEAN-5 Exchange Rates Returns Series

Series	Gaussianity Test Results (*p*-value)	Linearity Test Results (*p*-value)
IDR	0.000*	0.006
MYR	0.000*	0.006
PHP	0.000*	0.010
SGD	0.000*	0.006
THB	0.000*	0.006

Note: Both test statistics are distributed as N(0,1) and are taken as a one-sided test.
* denotes extremely small value.

Table 4
Bispectrum Test Results for ASEAN-5 Stock Returns Series

Series	**Gaussianity Test Results (*p*-value)**	**Linearity Test Results (*p*-value)**
JCI	0.000*	0.006
KLCI	0.000*	0.006
PCOMP	0.000*	0.028
STI	0.000*	0.006
SET	0.000*	0.036

Note: Both test statistics are distributed as N(0,1) and are taken as a one-sided test.
* denotes extremely small value.

Although Gaussianity and linearity tests are linked, a rejection of Gaussianity does not necessarily rule out linearity. If the underlying return series are linear, but not Gaussian, then the sample dispersion of $2\left|\hat{y}_{m,n}\right|^2$ should not differ significantly from the population dispersion of $\chi^2(2,\hat{\lambda})$, where $\hat{\lambda} = \{\hat{S}/P\} - 2$. The linearity test statistics examine whether the sample dispersion is significantly different from that of $\chi_2{}^2(2,\hat{\lambda})$. The third column of Table 3 reports the *p*-value for the 90 percent quantile bispectrum linearity test. The results reject the null hypothesis of a linear generating mechanism even at the 1% level of significance. This indicates the existence of non-linear dependencies within the daily returns series of the ASEAN-5 exchange rates under investigate. Similarly, the bispectrum linearity test results in Table 4 reveal strong evidence of non-linearity in all the ASEAN-5 stock returns series. It is important to note that the rejection of the null of linearity in the bispectrum test is a strong support for the presence of non-linearity (Barnett *et al.*, 1997).

Lukkonen-Saikkonen-Teräsvirta Test (LST Test)

The LST test results for the returns series of exchange rates and stocks of ASEAN-5 countries are summarised in Table 5 and 6 respectively. Table 5 shows that the null of no non-linearity has been strongly rejected (significant at 1% level) in all the exchange rates returns series under study. Thus, the findings based on LST test reinforce our conclusion drawn from the Hinich Bispectrum test that exchange rates exhibit non-linear dependencies.

As for the ASEAN-5 stock returns series, the null of no non-linearity has also been strongly rejected at standard significance level on the basis of LST test, indicating that the behaviour of all stock returns series in this region are also non-linear in nature. Again, this finding is in line with the earlier Hinich Bispectrum test.

Table 5
LST Linearity Test Results for ASEAN-5 Exchange Rates Returns Series

Series	p^a	d^b	LST statistic	p value
IDR	11	1	423.151	0.000*
MYR	10	1	321.312	0.000*
PHP	12	1	210.127	0.000*
SGD	12	2	306.760	0.000*
THB	10	10	931.239	0.000*

Notes: [a] The optimal autoregressive lag length *p* is determined by inspecting the PACF of the series.
[b] The optimal delay parameter *d* is chosen from the one that minimizes the *p* value of the implied LST (Luukkonen *et al.*,1988) statistic.
* denotes extremely small value.

Table 6
LST Linearity Test Results for ASEAN-5 Stock Returns Series

Series	p	d	LST statistic	p value
JCI	1	1	104.926	0.000*
KLCI	6	12	607.156	0.000*
PCOMP	1	12	12.774	0.001*
STI	1	1	66.353	0.000*
SET	1	12	32.111	0.000*

Notes: Refer Table 5.

V. CONCLUSIONS

The outcomes of our econometric investigation using the Hinich bispectrum test provide strong support for the presence of non-linearity in all the ASEAN-5 exchange rates and stock returns series. It is important to note that the rejection of the null of linearity in the bispectrum test is a strong support for the presence of non-linearity (Barnett et al., 1997). Further application of the LST test reinforces our conclusion that the financial time series data of ASEAN-5 exhibit non-linear dependencies. Besides complementing the Hinich bispectrum test, the results from the LST test suggest that all the returns series under investigate in this study (ASEAN-5 exchange rates and stock returns series) follow STAR-type non-linear process. Thus, these findings add to the current literature that financial markets are governed by non-linear dynamics, even in developing countries like ASEAN.

As mentioned earlier, if the underlying generating process for a time series is non-linear in nature, then it would be inappropriate to employ linear methods. On one hand, the results highlight the fact that researchers cannot take the linear assumption as granted, especially dealing with financial time series data. On the other hand, it points to the need to test for non-linearity as a preliminary diagnostic tool to determine the nature of the data generating process before any further empirical analysis. This study has strong implication on the empirical work of ASEAN-5 financial markets. Specifically, the results suggest the use of empirical methods that is more robust if the data generating process is non-linear, such as non-parametric cointegration test due to Bierens (1997), non-linear stationarity tests (Sarno, 2001; Chortareas *et al.*, 2002; Kapetanios *et al.*, 2003) and non-linear causality test (Baek and Brock, 1992).

REFERENCES

Abhyankar, A.H., Copeland, L.S. and Wong, W. (1995) Nonlinear dynamics in real-time equity market indices: evidence from the United Kingdom. *Economic Journal,* 105, 864-880.

Abhyankar, A.H., Copeland, L.S. and Wong, W. (1997) Uncovering nonlinear structure in real time stock market indexes: the S&P 500, the DAX, the Nikkei 225, and the FTSE 100. *Journal of Business and Economic Statistics,* 15, 1-14.

Ashley, R.A., Patterson, D.M. and Hinich, M.J. (1986) A diagnostic test for nonlinear serial dependence in time series fitting errors. *Journal of Time Series Analysis*, 7, 165-178.

Baek, E. and Brock, W. (1992) A general test for non-linear Granger causality: bivariate model. Working Paper. Iowa State University and University of Wisconsin at Madison.

Barkoulas, J. and Travlos, N. (1998) Chaos in an emerging capital market? The case of the Athens Stock Exchange. *Applied Financial Economics*, 8, 231-243.

Barnett, W.A., Gallant, A.R., Hinich, M.J., Jungeilges, J., Kaplan, D. and Jensen, M.J. (1997) A single-blind controlled competition among tests for nonlinearity and chaos. *Journal of Econometrics*, 82, 157-192.

Barnett, W.A. and Serletis, A. (2000) Martingales, nonlinearity, and chaos. *Journal of Economic Dynamics and Control*, 24, 703-724.

Baum, C.F., Barkoulas, J.T. and Caglayan, M. (2001) Non-linear adjustment to Purcahsing Power Parity in the post-Bretton Woods era. *Journal of International Money and Finance*, 20, 379-399.

Bierens, H.J. (1997) Nonparametric cointegration analysis. *Journal of Econometrics*, 77, 379-404.

Brock, W.A., Dechert, W.D., Scheinkman, J.A. and LeBaron, B. (1996) A test for independence based on the correlation dimension. *Econometric Reviews*, 15, 197-235.

Brock, W.A., Hsieh, D.A. and LeBaron, B. (1991) *Nonlinear dynamics, chaos, and instability: statistical theory and economic evidence*. Cambridge: MIT Press.

Brooks, C. (1996) Testing for non-linearity in daily Sterling exchange rates. *Applied Financial Economics*, 6, 307-317.

Campbell, J.Y., Lo, A.W. and MacKinlay, A.C. (1997) *The econometrics of financial markets*. Princeton: Princeton University Press.

Chortareas, G.E., Kapetanios, G. and Shin, Y.C. (2002) Non-linear mean reversion in real exchange rates. *Economic Letters*, 77, 411-417.

De Grauwe, P., Dewachter, H. and Embrechts, M. (1993) *Exchange rate theory: chaotic models of foreign exchange markets.* Oxford: Blackwell.

Hinich, M.J. (1982) Testing for Gaussianity and linearity of a stationary time series. *Journal of Time Series Analysis*, 3, 169-176.

Hinich, M.J. and Patterson, D.M. (1989) Evidence of nonlinearity in the trade-by-trade stock market return generating process. In W.A. Barnett, J. Geweke, and K. Shell (ed.) *Economic complexity: chaos, sunspots, bubbles and nonlinearity- international symposium in economic theory and econometrics*, pp.383-409. Cambridge: Cambridge University Press.

Hsieh, D.A. (1988) The statistical properties of daily foreign exchange rates: 1974-1983. *Journal of International Economics*, 24, 129-145.

Hsieh, D.A. (1989) Testing for non-linearity in daily foreign exchange rate changes. *Journal of Business*, 62, 339-368.

Hsieh, D.A. (1991) Chaos and nonlinear dynamics: application to financial markets. *Journal of Finance*, 46, 1839-1877.

Kapetanios, G., Shin, Y.C. and Snell, A. (2003) Testing for a unit root in the nonlinear STAR framework. *Journal of Econometrics*, 112, 359-379.

Luukkonen, R., Saikkonen, P. and Teräsvirta, T. (1988) Testing linearity against Smooth Transition Autoregressive models. *Biometrika*, 75, 491-499.

Mahajan, A. and Wagner, A.J. (1999) Nonlinear dynamics in foreign exchange rates. *Global Finance Journal*, 10, 1-23.

Opong, K.K., Mulholland, G., Fox, A.F. and Farahmand, K. (1999) The behavior of some UK equity indices: an application of Hurst and BDS tests. *Journal of Empirical Finance*, 6, 267-282.

Pesaran, M.H. and Potter, S.M. (1993) Nonlinear dynamics, chaos and econometrics: an introduction. In M.H. Pesaran and S.M. Potter (eds.) *Nonlinear dynamics, chaos and econometrics*, pp.vii-xiii. New York: John Wiley & Sons.

Sarantis, N. (1999) Modeling non-linearities in real effective exchange rates. *Journal of International Money and Finance*, 18, 27-45.

Sarno, L. (2000) Real exchange rate behaviour in high inflation countries: empirical evidence from Turkey, 1980-1997. *Applied Economics Letters*, 7, 285-291.

Sarno, L. (2001) The behavior of US public debt: a nonlinear perspective. *Economics Letters*, 74, 119-125.

Scheinkman, J. and LeBaron, B. (1989) Nonlinear dynamics and stock returns. *Journal of Business*, 62, 311-337.

Steurer, E. (1995) Nonlinear modeling of the DEM/USD exchange rate. In A.P. Refenes (ed.) *Neural networks in the capital markets*, pp. 199-211. New York: John Wiley & Sons.

Taylor, M.P. and Peel, D.A. (1997) Nonlinearities in real exchange rate adjustment during the recent float: empirical evidence and Monte Carlo analysis. Discussion Paper. Institute of Economics and Statistics, University of Oxford.

Taylor, M.P. and Peel, D.A. (2000) Non-linear adjustment, long-run equilibrium and exchange rate fundamentals. *Journal of International Money and Finance*, 19, 33-53.

Teräsvirta, T. (1994) Specification, estimation, and evaluation of Smooth Transition Autoregressive models. *Journal of the American Statistical Association*, 89, 208–218.

Vilasuso, J. and S. Cunningham (1996) Tests for nonlinearity in EMS exchange rates. *Studies in Nonlinear Dynamics and Econometrics*, 1, 155-168.

van Dijk, D., Teräsvirta, T., Franses, P. H. (2001) Smooth Transition Autoregressive models: a survey of recent developments. SSE/EFI Working paper in Economics and Finance, No. 380.