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Abstract

The empirical literature that tests for purchasing power parity (PPP) by focusing on the stationarity of real exchange rates has so far provided, at best, mixed results. The behaviour of the yen real exchange rate has most stubbornly challenged the PPP hypothesis and deepened this puzzle. This paper contributes to this discussion by providing new evidence on the stationarity of bilateral yen real exchange rates. We employ a non-linear version of the Augmented Dickey-Fuller test, based on an exponentially smooth-transition autoregressive model (ESTAR) that enhances the power of the tests against mean-reverting non-linear alternative hypotheses. Our results suggest that the bilateral yen real exchange rates against the other G7 and Asian currencies were mean reverting during the post-Bretton Woods era. Thus, the real yen behaviour may not be so different after all but simply perceived to be so due to the use of a restrictive alternative hypothesis in previous tests.

Key words: PPP, yen, real exchange rates, non-linear models, ESTAR models.

JEL classification: C23, F31.

Summary

Purchasing power parity (PPP) is the hypothesis that goods will trade at roughly the same price in different countries, once adjustments have been made for exchange rates. It is usually thought of as a long-run proposition. One way of examining this is to see if the real exchange rate (the exchange rate adjusted for relative prices in different countries) tends to return to a long-run average. This is known as mean reversion, and is one of the characteristics of a 'stationary' process. The empirical literature that tests for PPP by focusing on the stationarity of real exchange rates has so far provided, at best, mixed results. The behaviour of the yen real exchange rate, of all major currencies, has most stubbornly challenged the PPP hypothesis and deepened this puzzle. The yen real exchange rate in the post-WWII era has been characterised by a trend-like appreciation. Earlier attempts to reconcile the movement of the real yen with PPP theory included consideration of behavioural breaks, but the results were disappointing. As a consequence, Japan is often considered as the typical example of PPP failure.

In this paper we provide new evidence on the stationarity of bilateral yen real exchange rates and the validity of PPP by considering non-linear behaviour; that is, the possibility that the yen real exchange rate behaves differently at low and high levels. To do so we employ a non-linear version of the widely used Augmented Dickey-Fuller test, which tests for stationarity. This extension increases the ability of the test to detect stationarity when the underlying process is non-linear. The econometric model can accommodate the possibility that an implicit 'corridor regime' exists; within this corridor real exchange rates do not converge to their average values, but once they cross the thresholds of this regime they do begin to do so. This type of behaviour is consistent with the recent theoretical models where the non-linear behaviour of the real exchange rate implies a 'band of inaction'. Our results suggest that the bilateral yen real exchange rates against the other G7 and Asian currencies were mean reverting during the post-Bretton Woods era. In particular, the bilateral yen real exchange rate against the other G7 currencies appears to be stationary over our full sample (beginning in 1960), and this result does not change when we restrict our attention to the post-Bretton Woods era (with the exception of the yen/DM real exchange rate). Thus, the behaviour of the real yen may not be so different after all, but is simply perceived to be so due to the complicated nature of its behaviour. In addition to providing support for the PPP hypothesis, our results could motivate further research aiming to explain the underlying sources of yen's non-linear behaviour.

1 Introduction

Testing for purchasing power parity (PPP) by focusing on real exchange rate stationarity has been a major focus of empirical international finance. However, the existing evidence cannot be considered definitive. The empirical consensus in the 1980s that viewed real exchange rates as random walks shuttered the Casselian view of PPP. Although this consensus has been challenged itself by more recent studies that employ relatively new methodologies,[(1)] the weak connection between exchange rates and national price levels is not resolved. On the contrary, it seems that the division of researchers between the 'whittling down half lives' and the 'whittling up half lives' camps, as termed by Taylor (2001), is as vivid as ever before. The yen real exchange rate emerges as one of the major currencies refuting the proposition that the real exchange rate is mean reverting in the long run. Japan is often considered as the typical example of PPP failure. Thus, it is not surprising that the behaviour of the yen real exchange rate has been the focus of many studies using different data sets and statistical methodologies (eg, Lothian (1990), Ceglowski (1996) and Cheung and Lai (2001)).

The present paper contributes to this discussion by using new non-linear stationarity tests to provide evidence about the time-series properties of the bilateral yen real exchange rates. Recent contributions to the empirical literature investigate the presence of non-linear adjustment dynamics in the real exchange rate process (eg, Michael *et al* (1997), Taylor (2001)), thus motivating the use of such tests. We employ a non-linear version of the Augmented Dickey-Fuller (ADF) tests statistic that is based on a exponential smooth-transition autoregressive (ESTAR) model as developed by Kapetanios *et al* (2003).[(2)] If the true model involves non-linear dynamics that can be adequately approximated in some metric by a STAR (smooth-transition autoregressive)-type model then such non-linear tests are better equipped to reject the null hypothesis of a unit root as compared to the standard ADF test or other variants of it. In other words, our tests have greater power than the standard (ADF) tests for a particular mean-reverting non-linear alternative hypothesis. Such tests allow for the presence of a 'corridor regime' within which mean reversion does not occur, a feature consistent with the recent theoretical models where the presence of non-linearities implies a 'band of inaction' (for example, see Sercu *et al* (1995)).

The results of our analysis suggest that when allowing for a non-linear alternative the bilateral yen

(1) For surveys see Boucher Breuer (1994), Froot and Rogoff (1995), and Mark (2001).
(2) See also Blake and Kapetanios (2001) and Chortareas *et al* (2002).

real exchange rate against the other G7 currencies appears stationary for our full sample (1960 Q1-2000 Q4). Moreover this result does not change when we restrict our attention to the post-Bretton Woods era (with the exception of the yen/DM real exchange rate). Those results become more interesting when compared to those from corresponding ADF tests that provide limited evidence of stationarity. More importantly, the yen/dollar real exchange rate appears stationary during the current float, in contrast to most of the existing literature that has failed to produce evidence in favour of its stationarity. In addition, we consider the bilateral real exchange rate of the yen with the Asian and Pacific Rim currencies as motivated by various considerations, including geographic proximity and trade intensities. The non-linear tests are able to reject the non-stationarity null in at least twice the number of cases than the standard ADF tests during the current float period. The results of the analysis indicate that the inability to reject the unit root null in the bilateral yen real exchange rates may not necessarily reflect some extraordinary feature of this currency that refutes PPP, but rather the low power of tests against some alternative hypotheses or the presence of a 'corridor regime' in the real yen adjustment process.

The next section provides a literature review on evidence for the yen real exchange rate stationarity. Section 3 describes the testing methodology of Kapetanios *et al* (2003) and the data. Section 4 presents the results of our analysis. Section 5 discusses those results emphasising how they differ from existing evidence and why. Finally, Section 6 concludes.

2 Literature review

A stylised fact of the post-Bretton Woods float is the difficulty of distinguishing real exchange rates from random walks and provide evidence for PPP. Various methodological approaches have been used, including cointegration tests for exchange rates and prices, variance ratios tests, and unit root tests on real exchange rate series. Despite the theoretical appeal of PPP and the voluminous literature trying to uncover evidence of real exchange rate stationarity by considering longer time series, low frequency data, and new statistical methodologies, studies on PPP remain inconclusive. Less ambiguity seems to exist, however, for the yen real exchange rate which is shown on balance to be non-stationary (eg, Kim (1990), Cheung and Lai (1998), Koedijk *et al* (1998)). Not only have researchers not been able to reject the null of a unit root with drift in the yen real exchange rate (Rogoff (1996)) but also encountered difficulties in finding evidence for PPP when the yen was used as a base currency (eg, Papell and Theodoridis (1998)).

A number of possible reasons can be put forward for the failure to find evidence for PPP. These include traditional forms of price stickiness (Dornbusch (1976)) as well as explanations based on trade costs (eg, Dumas (1992)) and price discrimination (eg, Chari, Kehoe and McGrattan (2000)). The empirical literature on the time-series properties of the Japanese real exchange rate has primarily focused on real factors, and in particular on cross-country differences in productivity growth. The trend-like appreciation of the Japanese real exchange rate has been viewed as a typical case of the Balassa-Samuelson effect (eg, Rogoff (1996) and Ito *et al* (1999)).[3]

Departing from similar concerns Ceglowski (1996) attempts to capture the effects of relative productivity differentials on yen real exchange rates using the procedures suggested by Perron (1990) and Perron and Vogelsang (1992). Those tests and their modified versions enrich the ADF tests by allowing consideration of breaks in the mean as well as in the trend. The tests are applied to data spanning from the 1910s to 1991 and the non-stationarity result of the ADF tests is reversed in up to three out of five bilateral real exchange rates. All identified breaks in means, however, take place before the collapse of the Bretton Woods system, while the most recent break in trend is shown to take place in 1960. Since the current float is free from structural breaks the yen real exchange rate puzzle only deepens motivating further our analysis which is based on an alternative methodology.

Sequential extensions of the ADF tests suggested by Banerjee *et al* (1992) have been considered as better equipped to capture the trends breaks and shifts in the data. Cheung and Lai's (1998) analysis that uses such tests covers four bilateral yen real exchange rates among others. When the mean is included in the alternative hypothesis they can reject the unit root null in the bilateral yen real exchange rates in only one out of four cases (yen/DM) in the post-Bretton Woods period when the mean shift is included in the alternative hypothesis and in no case when the trend shift is included.

In general it has been difficult to reject the null hypothesis of a unit root in the real exchange rates when short data spans are considered; a difficulty more pronounced under the current float.[4] Cheung and Lai (1998), however, show that relatively short sample sizes, such as the post-Bretton

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(3) Obstfeld (1993) finds that the yen real exchange rate is characterised by a time trend and attributes it to productivity growth differentials between tradables and non-tradables sectors. Marston (1987) also focuses on labour productivity differentials.

(4) Lothian and Taylor (1996) show that for sample sizes as that of the current float the power of standard unit root tests is extremely low resulting to an inability of rejecting the potentially false null.

Woods era, do not necessarily render the rejection of non-stationarity impossible. They consider the bilateral real exchange rates of five industrialised countries including Japan using modified Dickey-Fuller tests suggested by Park and Fuller (1995) and Elliott *et al* (1996) to avoid the low-power problem. While both tests indicate that in the presence of a trend the yen/FF and yen/DM real exchange rates are stationary, they still cannot reject the null of a unit root in the yen/sterling and – more importantly – the yen/dollar real exchange rates.

The most popular recent method for circumventing the low-power problem of stationarity tests, however, is the use of panel methods. Applying such methods has typically allowed for the production of more evidence in favour of real exchange rate mean reversion (eg, Frankel and Rose (1996), MacDonald (1996), Oh (1996), Wu (1996), Papell (1997)).[(5)] Panel unit root tests, however, are not free from potential drawbacks including their excessive sensitivity to the country groupings and the panel size (eg, see Papell (1997)).

Cheung and Lai (2001) focus on the possibility of long-memory dynamics. They consider eight bilateral yen real exchange rates looking for evidence of fractional integration and find that the order of integration of all series considered is between zero and one. The use of fractionally integrated processes allows for long cycles and longer-term memory and provides a flexible enough framework simultaneously to describe large swings and mean-reverting dynamics that may characterise real exchange rate behaviour. Long-memory modelling, however, is essentially a purely statistical construct and the results should be interpreted with caution. The major difficulty is associated with giving a direct and meaningful economic interpretation to the non-integer order of integration.

There is also a fairly small[(6)] but growing literature on modelling exchange rates using non-linear models such as the TAR and STAR models (eg, Sarantis (1999), Baum *et al* (2001), Taylor *et al* (2001)). These papers, however, do not consider the interplay between non-linearity and non-stationarity since they simply assume that the series (or their differences) are stationary.

Despite the widespread consensus on the real yen's non-stationarity there exist studies providing evidence in favour of the opposite direction. Phylaktis and Kassimatis (1994) use black market

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(5) Exceptions include O'Connell (1998) and Chortareas and Driver (2001).

(6) For example, Sarantis (1999) mentions that '...there has been no attempt to investigate and model nonlinearities in real exchange rates and particular in effective exchange rates' (page 28).

exchange rates and find evidence for PPP but the results are stronger when Japan is excluded from their sample. Lothian (1990) finds evidence that the yen real exchange rates are mean reverting in very long samples. Interestingly, Lothian (1990) indicates that this adjustment process may not be continuous. The possibility of such a discontinuous adjustment process further motivates the use of a threshold model which can be approximated by a STAR-type model such as the one that we consider.

3 Methodology and data

3.1 Testing for a unit root against the non-linear $STAR$ model

Here we give an account of the testing methodology of Kapetanios *et al* (2003). Consider a univariate smooth transition autoregressive of order 1 ($STAR(1)$) model,

$$y_t = \beta y_{t-1} + \beta^* y_{t-1} \Phi\left(\theta; y_{t-d}\right) + \varepsilon_t, \; t = 1, ..., T; \; d \geq 1 \tag{1}$$

where $\varepsilon_t \sim iid\left(0, \sigma^2\right)$, and β, β^* are unknown parameters. It is assumed that y_t is a mean zero stochastic process. (For the case with non-zero mean and/or with a linear time trend see the discussion below.) $\Phi\left(\theta; y_{t-d}\right)$ denotes the transition function. We also assume that $\theta \geq 0$, and the delay parameter $d \geq 1$ is given. If θ is positive, then it effectively determines the speed of mean reversion. The representation **(1)** makes economic sense in that many economic models predict that the underlying system tends to display a dampened behaviour towards an attractor when it is (sufficiently far) away from it, but that it shows some instability within the locality of that attractor. A classic example is the floor and ceiling model of output analysed by Hicks (1950).

Following the literature on the $STAR$ models the popular exponential transition function is considered.

$$\Phi_E\left(\theta y_{t-d}\right) = 1 - \exp\left(-\theta y_{t-d}^2\right) \tag{2}$$

The exponential transition function is bounded between zero and 1, ie $\Phi : \mathbb{R} \rightarrow [0, 1]$, has the properties

$$\Phi_E\left(0\right) = 0; \; \lim_{x \rightarrow \pm\infty} \Phi_E\left(x\right) = 1$$

and is symmetrically U-shaped around zero.

Using **(2)** in **(1)** gives an exponential $STAR$ ($ESTAR$) model

$$y_t = \beta y_{t-1} + \beta^* y_{t-1}\left[1 - \exp\left(-\theta y_{t-d}^2\right)\right] + \varepsilon_t \tag{3}$$

The null hypothesis of a unit root is considered, which in terms of the above model implies that $\beta = 1$ and $\theta = 0$ (and thus $\Phi_E(\cdot) = 0$). Under the null, then **(3)** becomes the non-stationary linear $AR(1)$ model:

$$y_t = y_{t-1} + \varepsilon_t \tag{4}$$

Under the alternative of stationarity, θ is strictly positive and **(3)** becomes

$$y_t = \{\beta + \beta^* \Phi_E(\theta y_{t-d})\} y_{t-1} + \varepsilon_t, \;\; 0 < \Phi_E(\theta y_{t-d}) < 1 \tag{5}$$

We set $\beta = 1$ both under the null and under the alternative hypothesis. This assumption is consistent with earlier work (see eg Kapetanios *et al* (2003), Balke and Fomby (1997), Michael *et al* (1997), and Ioannides *et al* (2003)) but we also provide further justification after giving more details on the tests.

Under this assumption we can easily see that y_t would follow a near unit root in the region of $y_{t-d} = 0$ in which case $1 + \beta^* \Phi_E(\theta y_{t-d})$ would be close to unity. Large values of y_{t-d} on the other hand would result in an approximately linear $AR(1)$ process with the stable root $1 + \beta^*$ provided that $-2 < \beta^* < 0$. It is assumed that the latter is the case.

Explicitly then the null hypothesis is

$$H_0 : \theta = 0 \tag{6}$$

against the alternative[(7)]

$$H_1 : \theta > 0 \tag{7}$$

Obviously, testing the null hypothesis **(6)** directly is not feasible, since β^* is not identified under the null (see Davies (1977, 1987)).

Considering that the standard linear ADF test is not expected to be very powerful when the true process is stationary but non-linear, the direct testing framework can be developed. This involves estimating the following auxiliary regression

$$\Delta y_t = \delta y_{t-1}^3 + error \tag{8}$$

and using the following t-test statistic for **(6)**

$$NLADF = \frac{\widehat{\delta}}{s.e.\left(\widehat{\delta}\right)} \tag{9}$$

where $\widehat{\delta}$ is the OLS estimate obtained from the auxiliary regression and $s.e.\left(\widehat{\delta}\right)$ is the standard error of $\widehat{\delta}$. The test is motivated by the fact that the auxiliary regression is testing the significance

(7) Under the alternative **(7)** y_t is stable as $1 + \beta_* \Phi_E \left(\theta y_{t-d}\right) < 1$ for all y_{t-d}

of the score vector from the quasi-likelihood function of the $ESTAR$ model, evaluated at $\theta = 0$. The LM test of **(6)** against **(7)** also tests the significance of this term and is thus intimately related to the t-test that we consider. For a more thorough discussion of the test see Kapetanios *et al* (2003). Unlike the case of testing the linearity against the non-linearity for the stationary process the $NLADF$ test does not have an asymptotic standard normal distribution. Kapetanios *et al* (2003) provide details on the asymptotic properties of the test.

The main reason for assuming that $\beta = 1$ in the derivation of the test is to increase its power. Retaining the joint null hypothesis of $\beta = 1$ and $\theta = 0$, results in an F-test of the two parameters in the following auxiliary regression

$$\Delta y_t = \delta_1 y_{t-1} + \delta_2 y_{t-1}^3 + error \qquad \textbf{(10)}$$

being equal to zero rather than a t-test of a single parameter being equal to zero as in **(8)**. It is likely, however, that the F-test will be less powerful than the t-test. Under the plausible conjecture that the process is more persistent near its attractor (which in our simple case is $y_t = 0$), there is a better chance of finding δ_2 being significantly different from zero than finding δ_1 being significantly different from zero for two reasons, under the alternative hypothesis. First, δ_1 is likely to be close to zero anyway for persistent stationary processes. Second, the regressor y_{t-1}^3 is most prominent for large absolute values of y_{t-1} where the process is most likely to differ from a unit root process. We briefly consider this joint test in the discussion of the empirical results as a cross-check on the results obtained using the *NLADF* test.

The $NLADF$ test discussed above needs modifications to accommodate the process with a non-zero mean and a linear trend. In the case where the data have a non-zero mean such that $x_t = \mu + y_t$, the demeaned data $x_t - \bar{x}$ are used in **(1)**, where $\bar{x}$ is the sample mean. Similarly, for the case with a non-zero mean and non-zero linear trend such that $x_t = \mu + \delta t + y_t$ the demeaned and detrended data $x_t - \hat{\mu} - \hat{\delta} t$ are used in **(1)**, where $\hat{\mu}$ and $\hat{\delta}$ are the OLS estimators of μ and δ.

Asymptotic critical values of the $NLADF$ statistics for the above three cases, denoted $NLADF1$, $NLADF2$, $NLADF3$, respectively, have been tabulated via stochastic simulations with $T = 1,000$ and 100,000 replications, and presented in Table A below.

A relevant issue that emerges is the possibility of serial correlation in the error term. The presence of serial correlation may be dealt with by an augmentation similar to that undertaken for the

Table A: Asymptotic critical values for NLADF

	Asymptotic critical values		
sig. level	$NLADF1$	$NLADF2$	$NLADF3$
99%	-2.82	-3.48	-3.93
95%	-2.22	-2.93	-3.40
90%	-1.92	-2.66	-3.13

Dickey-Fuller tests. In particular, lagged differences of the dependent variable may be included in the regression and the asymptotic distribution of the t-test does not change.[8] Furthermore, many results that are valid for the linear case such as the data-dependent selection of the lag order of the augmentation extend to the non-linear test. In this paper we use a sequential testing procedure to determine the optimal lag order starting from a maximum lag order of 4. We note that the issues of demeaning and detrending as well as the issue of serial correlation can be dealt with similarly, if one wishes to consider the test based on the auxiliary regression **(10)** instead.

Finally, it is worth reporting some results from the extensive Monte Carlo analysis of Kapetanios *et al* (2003) on the performance of the NLDF test. The test has good size properties as the empirical rejection probabilities never deviate significantly from the nominal 5% significance level under the null hypothesis. It is considerably more powerful than the standard Dickey-Fuller unit root test for the case of a small θ (ie when θ lies between 0.01 and 0.1). In other words it is more powerful when θ lies close to its value under the null hypothesis, implying increased persistence for the non-linear process.

3.2 Data

We construct the bilateral yen real exchange rate against the *i-th* currency at time *t* ($q_{i,t}$) as $q_{i,t} = s_{i,t} + p_{J,t} - p^*_{i,t}$, where $s_{i,t}$ is the corresponding nominal exchange rate (*i-th* currency per yen), $p_{J,t}$ the price level in Japan, and $p^*_{i,t}$ the price level of the *i-th* country. Thus, a rise in $q_{i,t}$ implies a real yen appreciation against the *i-th* currency. The price levels are consumer price indices and all variables are in logs. All data are from the International Monetary Fund's *International Financial Statistics* in CD-ROM. The data are not seasonally adjusted. The first set of bilateral real exchange rates consists of those of the other G7 countries, ie, the United States,

(8) For a proof and detailed discussion see Kapetanios *et al* (2003).

the United Kingdom, Germany, Italy, France and Canada. The second set of bilateral real exchange rates are those of Australia, Korea Singapore, Malaysia, Philippines, New Zealand, Hong Kong, Indonesia, Thailand and Sri Lanka.

The Pacific Basin countries in our sample represent approximately one fourth (24%) of Japan's total trade, the United States represents another one fourth, and the remaining five G7 12%.[(9)] Furthermore, the experience of Japan may be of relevance for the Pacific Basin countries. Ito *et al* (1999) suggest that the pattern of industrial development in Asia may be similar to what has been called a 'flying geese pattern' with Japan as a leader followed by Hong Kong and Singapore, which are followed by Korea, followed in turn by Taiwan and Thailand, then by Indonesia and so on.

All data are quarterly, spanning from 1960 Q1 to 2000 Q4 and the bilateral nominal exchange rates against the currencies other than the US dollar are cross-rates computed using the US dollar rates. Previous research on the stationarity of real exchange rates in general, and of the yen real exchange rate in particular has used monthly, quarterly, and annual data. Typically, lower frequency data were used when longer time spans were considered. Our sample is shorter compared to studies whose data span measures in centuries or so (eg, Lothian (1990), Ceglowski (1996)) but almost one decade longer than the existing studies focusing on the post Bretton-Woods real yen behaviour. Those analyses use annual and monthly data respectively. Using quarterly data, however, seems a good compromise, since it allows comparability of our results with most of the existing literature.[(10)]

4 Results

We include a trend in the unit root tests we perform subsequently in order to account for the presence of a trend in the bilateral yen real exchange rate. The asymptotic critical values given in Table A refer to large samples. Since the tests in this section were applied to small samples we

(9) Data are from OECD's Statistical Compendium.

(10) Recently, Taylor (2001) points to the implications of considering data whose frequency does not match that of the underlying arbitrage process. Clearly, considering low frequency data is not the best strategy when the hypothesised adjustment process is a high frequency one. Temporal aggregation problems may lead to biased coefficients and low power in standard unit root tests. While such considerations are valid we proceed with the quartely data to make our results comparable with those of the existing literature. We should note, however, that if the true model is non-linear high frequency data will make it easier to pick up the non-linear adjustment. On the other hand, if the adjustment process is a long-memory one, then it will be picked up more easily by longer data spans of low frequency.

calculate the test critical values for samples of 160 and 100 observations (these are roughly the sizes of most samples considered). The 5% and 1% critical values for the third version of the test (demeaned and detrended) are 3.38 and 3.95 respectively for samples of 160 observations and 3.37 and 3.94 for samples of 100 observations. Thus, the differences between these critical values and those reported in Table A are negligible and in no case affect our results and conclusions.

Table B provides the results from applying the tests described in Section 3.1 to the real exchange rates of the G7 countries, covering our full sample. These tests as well as the tests that we subsequently perform employ the version of the test that uses detrended data. The non-linear version of the ADF (NLADF) tests show that all six bilateral real exchange rates are stationary either at the 1% or the 5% level of significance. Furthermore, the choice of lag augmentation does not affect the results. That is, all six series appear stationary when both a four-lag scheme is imposed and when the choice of the optimal number of lags occurs through an optimisation routine that consecutively tests down from a higher to a lower number of lags. On the other hand, the standard ADF tests indicate stationarity for only two real exchange rates, namely sterling and the Canadian dollar.

Table B: 1960 Q1 to 2000 Q4

	DF	ADF(4)	ADF(A)	NLDF	NLADF(4)	NLADF(A)
US	−1.666	−2.768	−2.675	−2.618	−3.928*	−3.850*
Germany	−2.669	−2.960	−2.904	−3.222	−3.728*	−3.504*
France	−2.412	−3.115	−3.072	−2.939	−3.947**	−3.828*
Italy	−2.015	−2.853	−3.011	−3.230	−4.606**	−4.848**
UK	−2.112	−3.050	−4.079**	−2.811	−3.986**	−4.603**
Canada	−2.309	−3.748*	−4.082**	−2.537	−3.848*	−3.838*

When we restrict our focus on the post-Bretton Woods era in Table C the results of the NLADF tests (of Table B) remain robust. The only exception seems to be the yen/DM real exchange rate that displays a unit root under both the linear and non-linear alternative hypotheses. The standard ADF tests provide evidence of stationarity for up to three bilateral real exchange rates, namely Italy, the United Kingdom, and Canada. Only the evidence for the yen/Canadian dollar real exchange rate, however, appears to be robust to the choice of the lag augmentation. In contrast, the results of the NLADF tests that demonstrate stationarity in five out of the six real exchange rates are invariant to the lag order selection. It is interesting that our analysis allows rejection of the unit root null for the yen/dollar real exchange rate despite the notable variability of the yen against the dollar during the sample which includes the 1980s.

Table C: 1974 Q1 to 2000 Q4

	DF	ADF(4)	ADF(A)	NLDF	NLADF(4)	NLADF(A)
US	−1.785	−2.776	−2.692	−2.825	−4.227**	−4.181**
Germany	−2.234	−2.367	−2.460	−2.639	−3.084	−2.894
France	−2.192	−2.687	−2.784	−2.770	−4.019**	−4.495**
Italy	−2.220	−3.082	−3.664*	−3.242	−4.758**	−5.305**
UK	−1.982	−2.812	−3.937*	−2.571	−3.798*	−4.770**
Canada	−2.019	−3.436*	−3.801*	−2.590	−4.042**	−4.237**

Turning to the Asian and Pacific economies in Table D, we obtain evidence of stationarity for six out of the nine countries when we consider the full sample period. Those results are invariant to the lag length selection. The countries for which we fail to reject the null hypothesis of a unit root are Korea, Malaysia and Sri Lanka. The results of the ADF tests depend on the method of lag augmentation. When the endogenous lag selection method is used then the ADF test rejects the null hypothesis of a unit root in only three cases out of nine. The countries for which the null hypothesis is rejected are Australia, Korea and the Philippines. Interestingly, the null hypothesis is rejected for Korea using the ADF test but not using the NLADF leading us to believe that there might be a degree of complementarity between the two tests. In other words the two tests seem to be powerful against different directions of deviation from the null hypothesis, as expected. Turning to the floating exchange rate period, the NLADF test rejects the null hypothesis in five out of nine cases (Table E). These countries are Australia, Korea, Hong Kong, Indonesia and the Philippines. This result is quite robust to the lag-length selection method employed. For example, when four lags are used, the result changes in only one country (Korea). The ADF tests, on the other hand, reject the non-stationarity null in up to two out of nine cases (and only when the automatic lag selection method is used).[11]

5 Discussion

Our results indicate that when the alternative hypothesis in the unit root tests can accommodate the presence of non-linear adjustment the yen bilateral real exchange rates appear to be

(11) As a cross-check on our analysis we have considered the test based on the auxiliary regression **(10)**. Results (available upon request) show very similar patterns. In particular for all non-linear tests the only differences were for: (i) Germany for the whole sample where the joint test did not reject but the NLADF did; (ii) Korea for the whole sample where the NLADF test did not reject but the joint test did; and finally (iii) Korea for the subsample (1974-2000) where the joint test does not reject but the NLADF test does.

Table D: 1960 Q1 to 2000 Q4

	DF	ADF(4)	ADF(A)	NLDF	NLADF(4)	NLADF(A)
Australia	−2.634	−3.587*	−4.652**	−3.793*	−5.106**	−5.812**
Korea	−2.931	−3.880*	−3.651*	−2.621	−3.331	−3.106
Hong Kong	−1.472	−2.030	−1.977	−2.853	−4.228**	−4.199**
Singapore	−1.944	−3.435*	−3.329	−2.105	−3.612*	−3.592*
Malaysia	−2.373	−3.565*	−3.325	−2.359	−3.328	−3.190
Indonesia	−2.338	−2.756	−2.521	−2.906	−4.624**	−4.283**
Thailand	−2.532	−3.281	−3.243	−2.975	−3.777*	−3.721*
Philippines	−3.566*	−4.216**	−3.761*	−3.938**	−5.036**	−6.472**
Sri Lanka	−0.782	−1.282	−1.578	−1.128	−1.761	−2.229

Table E: 1974 Q1 to 2000 Q4

	DF	ADF(4)	ADF(A)	NLDF	NLADF(4)	NLADF(A)
Australia	−2.136	−2.944	−3.541*	−3.075	−4.186**	−4.644**
Korea	−2.879	−3.215	−3.441*	−2.678	−3.132	−3.448*
Hong Kong	−1.472	−2.030	−1.977	−2.853	−4.228**	−4.199**
Singapore	−1.707	−3.040	−3.145	−1.827	−3.095	−3.274
Malaysia	−1.894	−2.797	−2.643	−2.087	−2.961	−2.878
Indonesia	−2.934	−3.226	−2.902	−3.004	−4.569**	−4.186**
Thailand	−2.305	−2.830	−2.848	−2.663	−3.302	−3.328
Philippines	−3.196	−3.257	−3.188	−4.767**	−5.407**	−6.721**
Sri Lanka	−1.902	−2.631	−3.254	−1.586	−2.232	−2.868

mean-reverting. Those findings are consistent with recent theoretical analyses that point to various rigidities including transportation costs and monopolistic price-setting. For example, Sercu *et al* (1995) modify the Lucas (1982) model to allow for the presence of transactions costs, and show that the international imbalances between marginal utilities of consumption (the ratio of which corresponds to the real exchange rate) do not adjust if they are sufficiently small relative to the transaction costs. Dumas (1992) provides a model where spatial market separation and transaction costs give rise to a band of inaction. Deviations from PPP are persistent but mean reversion through a non-linear adjustment process finally occurs. Uppal (1993) provides a similar non-linear channel of real exchange rate adjustment.

Our findings are also consistent with other recent empirical approaches that consider non-linear adjustment dynamics. Baum *et al* (2001) find evidence for weak PPP in the CPI-based yen/dollar real exchange rate. This study, as well as those by Balke and Fomby (1997) and Michael *et al* (1997), focuses on cointegration between nominal exchange rates and price indices using threshold cointegration techniques. All those analyses, however, assume that the real exchange rate processes themselves are stationary and ergodic and focus on modelling the non-linear adjustment. Our analysis differs from the above in that we test for stationarity by examining for the presence of unit root in the real exchange rate process itself. Identifying the exact source of non-linearities in the yen real exchange rates is beyond the scope of this paper.

A typical feature in the literature is the difficulty of producing evidence in support for PPP using the yen as the numeraire currency. For example, Papell and Theodoridis (1998) conduct both panel and univariate unit root tests using the US dollar and the DM as base currencies and find stronger evidence for PPP in panels when the DM is used as the numeraire currency. Using the yen as a base currency only increases the difficulty of finding evidence of real exchange rate stationarity. Koedijk *et al* (1998) use an alternative panel methodology that allows consideration of individual country effects when testing for the relationship between exchange rates and prices. Similarly to the previous authors, they obtain stronger evidence for PPP when the DM rather than the US dollar is used as a numeraire. Using the Japanese yen, however, provides again the weakest evidence for PPP. Interestingly, the use of the the yen as the base currency throughout this study does not hinder the ability to produce evidence for stationarity for both the G7 bilateral real exchange rates and those of other Asian and Pacific countries.

The non-linear unit root tests results always provide more evidence in support of the bilateral real yen stationarity when considering the full sample as compared to the current float only. This is consistent with Rogoff's (1996) observation that the most convincing evidence on PPP comes from data sets employing at least some fixed exchange rate data. Mussa (1986) also suggests that given the relatively similar price level paths under fixed and floating exchange rates most of the variability in real exchange rates can be accounted for by changes in the nominal exchange rates. Whether the presence of this regularity in our findings is a feature of the longer data span or due to the fixity of the exchange rates, however, is a matter for further research.

6 Conclusion

If there is a G7 real exchange rate that makes the rejection of the unit root hypothesis difficult, this is the yen real exchange rate. Existing research has responded either by accepting this result as a fact (typically attributing the yen's behaviour to Balassa-Samuelson effects) or by considering longer data spans and – more recently – by utilising different statistical techniques that may account for the series behaviour more appropriately. Focusing on possible non-linearities has been one direction within the last strategy.

We contribute to this discussion by considering the stationarity of bilateral yen real exchange rates using new unit root tests that incorporate a non-linear alternative hypothesis. That is, in contrast to other recent studies that assume real exchange rate stationarity and try to explain the non-linear adjustment, we check for the presence of non-linear dynamics in the process itself. Such considerations are consistent with recent theoretical developments that emphasise the role of transactions costs and monopolistic pricing as possible explanations for the presence of 'inaction bands' and non-linear mean reversion of real exchange rates.

Our results show that the null of non-stationarity is rejected when the alternative hypothesis in ADF-type unit root tests is modified to allow for the presence of non-linearities. The non-linear ADF tests provide stationarity evidence for the Japanese real exchange rate in at least twice as many cases compared to the standard ADF tests during the post-Bretton Woods era. When considering our full sample (starting from 1960) all six bilateral yen real exchange rates against the other G7 countries emerge as mean reverting. Similar results in favour of PPP emerge when we consider the bilateral yen real exchange rates with other Asian and Pacific countries. These results become more intriguing when one recalls that earlier research encountered extra difficulties in uncovering evidence for PPP when the yen was used as the base currency.

Providing an explicit explanation for the underlying sources of the non-linear adjustment process in the yen real exchange rates is beyond the scope of this paper and constitutes the subject of further research. The present paper makes the point that the yen real exchange rate behaviour may not be so particular after all. That is, it may simply be the use of tests that incorporate an inappropriate alternative hypothesis that is responsible for what has been considered 'exceptional' real exchange rate behaviour. Further work on this research agenda could utilise the non-linear unit root test considered in this paper to examine puzzles related to empirically observed non-stationarity of related macroeconomic variables such as, eg, inflation rates.

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