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Structural changes and unit roots in Japan's macroeconomic time series: is real business cycle theory supported?

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Abstract

This paper aims to detect temporal and continuous structural changes in the major Japanese macroeconomic time series by means of Yamamoto's (1996) augmented step-wise Chow test, and to clarify the stationarity and/or non-stationarity of these series by conducting unit root tests. It also aims to verify empirically that a model assuming no structural change is not likely to reject a null hypothesis even when a true model contains a structural change. Structural changes are assumed to contain not only changes in the parameters of the drift term and the time trend, but also changes in other parameters. The results favor the existence of real business cycles.

JEL classification: C19; E19

Keywords: Structural changes; Step-wise Chow test; Unit roots; Macroeconomic time series; Real business cycles

1. Introduction

The stochastic parts in regression analysis of time series data are sometimes non-stationary, and a problem called spurious regression occurs, though the parts have been assumed stationary a priori. Even when the estimation results are distorted, they appear good, and therefore we are in danger of falling into the error of regarding the regression as correct. In order to avoid such a danger, it is necessary to test whether the data in each time series is stationary or not, in advance. Since Fuller (1976) and Dickey and Fuller (1979,

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1981) advocated tests (Dickey–Fuller test, DF test and augmented Dickey–Fuller test, ADF test) in which a null hypothesis is a non-stationary process with a unit root (difference stationary process), and an opposing hypothesis is a trend stationary process, various testing methods have been developed. Nelson and Plosser (1982) applied their test to the American economy, and verified that almost all economic time series such as real GNP follow a non-stationary process with a unit root. Their results seemed to provide strong empirical evidence for the real business cycle theory that was advocated by Kydland and Prescott (1982) and Long and Plosser (1983), and stimulated a vigorous response. Phillips (1987) and Phillips and Perron (1988) weakened a strong assumption on the error term, and extended the DF test to be a more general test (PP test). However, the new PP test did not alter the result of Nelson and Plosser (1982), even using the same data as Nelson and Plosser (1982).

On the contrary, Kwiatkowski et al. (1992) devised a test that reversed the null hypothesis and the opposing hypothesis (KPSS test), and verified that only half of economic time series had a unit root, using the same data as Nelson and Plosser's (1982). This implied that Nelson and Plosser's (1982) evidence for real business cycle theory was not conclusive. In fact, Dickey–Fuller type tests do not necessarily have high reliability, because their testing power is very weak when a characteristic root is near unity, and they ignore structural changes in time series.

More strict methods of unit root tests which clearly consider structural changes in time series were first researched by Perron (1989). He proved that the ADF test does not reject a null hypothesis of unit root even when a true model follows a trend stationary process, if there is a structural change such as a change in a constant term or a refraction in slope at an exogenous point in time. He verified that almost all US economic time series follow a trend stationary process, using the same data as Nelson and Plosser's (1982). His result was almost perfectly contradictory to Nelson and Plosser's (1982), and provided strong evidence against real business cycle theory. Perron's (1989) proposal caused great controversy, and stimulated much similar research to integrate a structural change test and a unit root test.

Though Perron (1989) regarded a structural change as given exogenously at a point in time, Christiano (1992), Zivot and Andrews (1992), and Banerjee et al. (1992) criticized this, proposing unit root tests that detect a structural change endogenously, and conducted empirical analyses by using unit root tests devised by themselves. Kunitomo (1996a,1996b) studied the classes of such test statistics as likelihood test, Wald test, and Lagrangian test concerning unit root and cointegration hypotheses, and proposed a unit root test which is able to detect multiple structural changes in trend. These Perron-type methods consider only temporal structural breaks in drift and trend terms, and hence have a defect that they rarely capture true structural breaks correctly.

On the other hand, in order to separate a structural change test and a unit root test, Yamamoto (1996) proposed an augmented step-wise Chow test. Compared with the Perron-type methods, it can capture true and whole features of structural changes on the basis of more general and rigorous analysis. It's merits are the following: First, it considers not only structural changes in a drift term and a time trend but also changes in the regression coefficients of lag structure. Second, whether the type of change is a kink or a jump, it takes into account not only a temporal change but also a sequence of continuous changes. Third, it can capture not only once-and-for-all change but also a plurality of changes. Fourth, it can properly treat a structural change from a unit root process to a trend stationary process, and vice versa.

The objectives of this paper are to detect temporal and continuous structural changes in the major Japanese macroeconomic time series by means of an augmented step-wise Chow test based on a method of Yamamoto (1996); to clarify stationarity and/or non-stationarity of macroeconomic time series by conducting unit root tests; and to induce their economic implications.

In Section 2, we first explain two kinds of unit root tests to test the stationarity and non-stationarity of time series data, which have usually been used when a structural change is assumed not to exist. Next, we briefly explain two methods of conducting a structural change test and a unit root test, integrating and separately, respectively. As one of the latter, we introduce an augmented step-wise Chow test based on Yamamoto's (1996) method. In Section 3, we first conduct ADF and PP tests for thirteen Japanese macroeconomic time series data on the assumption of no structural change. Next, on the reverse assumption that there exist structural changes we detect time points of structural changes endogenously by means of an augmented step-wise Chow test. We select the optimal time lag with the aid of AIC. In divided periods, in which the structure is significantly stable, we again conduct ADF and PP tests for the time series data, and compare the results of the tests with those of Yamamoto and Zhai (1995). In the last section, we summarize with some concluding remarks.

Structural changes are significantly detected for all the time series except the Yen–Dollar exchange rate. A null hypothesis of unit root is rejected for seven time series in some time period. But it is not rejected for real time series such as real GDP, real private consumption, real total investment, and industrial production index, implying robust evidence for real business cycles even after considering structural changes. It is rejected for neither the Nikkei average stock price index nor the Yen–Dollar exchange rate, in which cases a typical random walk process is usually supposed to dominate.

A null hypothesis of unit root is rejected in more cases when structural changes are assumed to exist than when no structural change is assumed to exist. This result supports Perron's (1989) theorem that a unit root test which ignores a structural change when it exists, does not reject a null hypothesis of unit root even if a true model is trend stationary. Some trend stationary series change to difference stationary or vice versa after a structural break, implying that the Perron-type approach to integrate a structural change test and a unit root test fails to capture a true change, and that it is desirable to apply Yamamoto's (1996) method.

2. Structural changes and unit root tests

2.1. Unit root tests assuming no structural change: ADF and PP tests

Taking notice of the fact that a boundary of whether a stochastic process $\{y_t\}$ is stationary or non-stationary is nothing but a case for a unit root, Fuller (1976) and

Dickey and Fuller (1979) developed a test for stationarity, i.e. the Dickey–Fuller test. Dickey and Fuller (1979) considered the most simple first order autoregressive model, AR(1).

The DF test is valid only under the assumption that there exists no serial correlation in random disturbances. However, this assumption is not usually satisfied. Dickey and Fuller (1981), then, extended the model to that with a random disturbance term subject to the pth order autoregressive process, AR(p), and devised a test which modified the τ test, which is called the augmented Dickey–Fuller test. The ADF test considers both a model with a drift term (constant term) α and a model with a drift term and a time trend γt as Eq. (2.1), where Δ denotes a difference operator.

$$\Delta y_t = \alpha + \gamma t + b_1 y_{t-1} + \sum_{i=2}^{p} b_i \,\Delta y_{t-i+1} + \varepsilon_t \qquad \varepsilon_t \sim \text{i.i.d.}(0, \sigma^2) \tag{2.1}$$

Though Dickey and Fuller (1979) did not consider a non-linear time trend, we add a quadratic time trend κt^2 to the model.

$$\Delta y_t = \alpha + \gamma t + \kappa t^2 + b_1 y_{t-1} + \sum_{i=2}^{p} b_i \,\Delta y_{t-i+1} + \varepsilon_t \qquad \varepsilon_t \sim \text{i.i.d.}(0, \sigma^2) \tag{2.2}$$

The ADF test requires not only the assumption that the error term ε_t is not correlated, but also the stronger assumption that it is independently and identically distributed (i.i.d.). On the other hand, Phillips and Perron (1988) proposed a method that tests the above models non-parametrically under the more general assumption that accepts dependency of an error term on time, and heteroscedasticity of variance. This is named the PP test. They calculated the value of Z_α that modifies the influence of autocorrelation of the error term in order for t-value to follow the τ distribution. Since Z_α follows an asymptotic distribution, one needs to use the test statistics in the case of an infinite number of samples, as shown in Fuller (1976). These unit root tests are not necessarily robust, and it is desirable to use multiple tests. Hence we use both ADF and PP tests.

DeJong et al. (1992) pointed out that a Dickey–Fuller type test suffers from the danger of committing the second type mistake that it is not able to reject a null hypothesis even when it is wrong if a characteristic root is near unity, and therefore the testing power gets weaker. To avoid this mistake, MacKinnon (1994) and Hatanaka and Koto (1995) proposed a testing method that utilizes P-values instead of a method that sets a rejection level and judges its relation to a critical value. Therefore we had better use judgment based upon not only t-value but also P-value, even when we conduct ADF and PP tests.

2.2. Methods unifying a structural change test and a unit root test

Perron (1989) devised a unit root test that incorporates a change in a drift term and a kink of a time trend in a linear model exogenously, and proved Theorem 1 that the ADF test is not able to reject a null hypothesis of unit root, and creates a ''spurious unit root'' when a true model is trend stationary and there is a structural change. With the same data as Nelson and Plosser (1982), he examined a null hypothesis of unit root in a model that accompanies a structural change to obtain the result that a null hypothesis was rejected for 11 out of 13 sets of time series data. He concluded that most American major economic time series data were subject to a trend stationary process that accompanies a structural change.[1]

Perron's (1989) method suffers from arbitrariness in the sense that it introduced a structural break exogenously not endogenously. Christiano (1992) criticized Perron's exogenous treatment of a structural change, and devised a method with which structural changes in a drift term and a trend can be detected endogenously, and proposed a test whose null hypothesis is a unit root process without a structural change, and whose opposing hypothesis is a stationary process with a structural change. Zivot and Andrews (1992) proposed a test whose null hypothesis is a unit root process without any change in a drift term, and whose opposing hypothesis is a trend stationary process with a structural break. Their test can detect a time point of a structural change endogenously, and its asymptotic distribution is constant regardless of the time points of structural changes. In order to conduct a unit root test which is able to find endogenously an unknown time point of structural change, Banerjee et al. (1992) proposed three kinds of unit root tests: firstly a recursive test that is extended on the basis of a structural stability test of Brown et al. (1975) which uses recursive residuals; secondly a rolling test that shifts a partial testing period successively among the whole sample period; and thirdly a sequential test that conducts t tests or Quandt likelihood ratio tests while shifting a time point of a structural change among the whole sample. Kunitomo (1996a) studied unit root and cointegration hypotheses in cases where a structural change exists, and proposed the classes of such test statistics as likelihood ratio test, Wald test, and Lagrangian test.

These tests have the merit of being able to conduct a structural test and a unit root test at the same time, and of being able to yield more rigorous and correct results than simple ADF or PP test. However, most of them except Banerjee et al. (1992) test have the problem that they can not necessarily fully detect true structural changes, because they consider only a temporal structural change in a drift term and a time trend.

2.3. Separation of a structural change test from a unit root test

Hatanaka and Yamada (1999) questioned the tests that introduce an unknown structural change into a null hypothesis, though restricting the structural change to a change in a drift term and a trend term. They proposed a two-stage method of estimating first the time point of a structural change with a structural test that is appropriate to either

[1] Soejima (1994) applied the classical Perron (1989) test, which assumed one structural break exogenously, to Japan's eight quarterly series and obtained the result that real GDP, real private consumption, industrial production, and the call rate were trend stationary.

I(0) or I(1), and then conducting a unit root test during divided stable periods. In this direction some research has been conducted to separate a structural change test and a unit root test.

Takeuchi (1992) detected time points of a structural change by means of step-wise Chow test, and then conducted a unit root test in each divided period in which a structural change is supposed not to exist. The Chow test statistics used by Takeuchi (1992) do not converge to a χ^2 distribution even in a large sample, and therefore one can not apply usual critical values in testing a null hypothesis.

Extending an idea of Toda and Yamamoto (1995), Yamamoto (1996) proposed an augmented step-wise Chow test in order to use usual critical values regardless of whether a data generating process (DGP) is trend stationary or difference stationary. Yamamoto and Zhai (1995) conducted an augmented step-wise Chow test based on a method of Yamamoto (1996) for six Japanese economic time series such as GNP, the money supply, etc., and detected significantly a structural change in all the series but the Nikkei average stock price index, and concluded that two series were trend stationary before the structural change and four after it.

This paper utilizes the augmented step-wise Chow test based on a method of Yamamoto (1996) to detect structural changes endogenously, and then conducts ADF and PP tests in divided periods in which any structural change is supposed not to exist. We apply Yamamoto's (1996) method more suitably than Yamamoto and Zhai (1995) did.

Actual structural changes are not only a change in a drift term or in a trend term but also include any changes in the structural coefficients of the model, or a change from a unit root process to a trend stationary process and vice versa. They usually occur not instantaneously at one point in time, but successively over a certain time interval, in spite of whether the type of structural change is classified as a jump or a kink. When a structural change occurs successively, a model assuming instantaneous change generates arbitrary shocks and distorts the test results. Therefore, one needs to detect first whether a structural change is successive or instantaneous. If the change is successive, one needs to apply a structural change test that is able to capture a successive change correctly, and to conduct a unit root test in a stable period in which no structural change is significantly detected. Moreover, one should pay attention to the number of structural changes, i.e. it should not be assumed a priori that there is only one. An augmented step-wise Chow test based on the method of Yamamoto (1996) is one of the structural change tests which satisfy these conditions.

2.4. The augmented step-wise Chow–Yamamoto test

Following Yamamoto (1996), as summarized in the Appendix, let a model for a stochastic process $\{y_t\}$, at a point (T_B) of a structural change and before that $(t = 1, 2, \ldots, T_B)$, be a pth order AR(p) model with a drift term α and a trend term γt.

$$y_t = \alpha + \gamma t + \sum_{i=1}^{k} a_i y_{t-i} + \varepsilon_t \tag{2.3}$$

In order to adjust least squares estimates so as to follow an asymptotic normal distribution when the above equation is likely to have a unit root, additional explanatory variables, 1^*, t^*, $b_{p+1}y_{t-p-1}$ are introduced. Rewriting it with a difference operator Δ gives the following.[2]

$$\Delta y_t = \alpha + \gamma t + b_1 y_{t-1} + \sum_{i=2}^{p} b_i \,\Delta y_{t-i+1} + \alpha^* 1^* + \gamma^* t^* + b_{p+1} y_{t-p-1} + \varepsilon_t,$$

$$b_1 = \sum_{i=1}^{p} a_i - 1, \qquad b_k = -\sum_{i=k}^{p} a_i \,(k = 2, 3 \cdots, p), \qquad 1^* = 1 + T^{-\lambda} v_{1t},$$

$$t^* = t + T^{-\lambda} v_{2t}, \qquad v_{it} \sim \text{i.i.d.}(0, \sigma_i^2) \quad (i = 1, 2), \qquad 0 < \lambda < \frac{1}{2} \tag{2.4}$$

If $b_1 = 0$, then a unit root exists, and if $b_1 < 0$, then a stationary root exists. v_{it} $(i = 1, 2)$ is independent from ε_t and is serially uncorrelated white noise that is calculated as pseudo random numbers with variance normalized as unity.

Similarly, let a model after a point (T_{B}) of a structural change ($t = T_{\mathrm{B}} + 1$, $T_{\mathrm{B}} + 2, \ldots, T_{\mathrm{B}} + T$) be a pth order AR(p) model with drift and trend terms (as attaching # seal).

$$\Delta y_t = \alpha^{\#} + \gamma^{\#} t + b_1^{\#} y_{t-1} + \sum_{i=2}^{p} b_i^{\#} \,\Delta y_{t-i+1} + \alpha^{*\#} 1^* + \gamma^{*\#} t^* + b_{p+1}^{\#} y_{t-p-1} + \varepsilon_t \tag{2.5}$$

In these models, the null hypothesis that a structural change does not exist and the opposing hypothesis that it does are expressed as follows.

$$H_0 : \alpha = \alpha^{\#}, \;\; \gamma = \gamma^{\#}, \;\; \text{and} \;\; b_k = b_k^{\#} \quad (k = 1, 2, \cdots, p) \tag{2.6}$$

H_1: at least one equation above does not hold.

Chow's F test statistics follow the F distribution whose degrees of freedom are $(p + 2, T - 2(p + 5))$.

3. Empirical analyses of unit root tests

3.1. Data

Among previous research in Japan that conducted unit root tests assuming a structural change are Takeuchi (1992), Iwamoto and Kobayashi (1992), Soejima (1994), Yamamoto and Zhai (1995), Kunitomo (1996b), Miyakoshi and Tsukuda (1998) and Ohara (1999).

[2] Yamamoto (1996) assumes $0 < \lambda < 1/2$, since the central limit theorem does not hold when $\lambda \geq 1/2$ or $\lambda \leq 0$. He also assumes the same value for λ to conduct a simultaneous test for coefficient constraints. However, Yamamoto and Zhai (1995) used different values for λ in the Eq. (2) to conduct individual tests for coefficient constraints.

$$1^* = 1 + v_{1t}/T^{-0.25}, \quad t^* = t + v_{2t}, \quad v_{it} \sim \text{i.i.d.}(0, \sigma_i^2) \quad (i = 1, 2)$$

. They used different values: $\lambda = 0.25$ in the former equation and $\lambda = 0$ in the latter equation.

In order for a comparison with the results of these researches as well as Nelson and Plosser (1982) to be as meaningful as possible, we use 13 macroeconomic series; 5 using quarterly data, and 8 using monthly data. The former covers nominal GDP (billion Yen), real GDP (billion Yen, 95 year prices), real private consumption (billion Yen, 95 year prices), real private investment (gross capital formation; billion Yen, 95 year prices), GDP deflator (95 year prices), of which the sample period is from 1955:2 to 1998:2, and of which the sample number is 173. The latter contains the index of industrial production (IIP, 95 year basis), the Consumer Price Index (CPI, 95 year basis), the unemployment rate, M1 (billion Yen), M2 + CD (billion Yen), the call rate (overnight), the Nikkei average stock price index, and the Yen–Dollar exchange rate, the sample period being from 1955/1 to 1999/8, and the sample number 536.

All the data are taken from the "NEEDS" database (Nikkei general economic file) of Japan Economic Newspaper (Nihon Keizai Shinbun). All the data are seasonally adjusted in principle. In order to reduce the effect of trends, we use natural logarithms of all the data except the call rate, because they have an increasing or decreasing trend.

We carried out most of the analyses below using Time Series Processor (TSP), but we wrote our own program for some test procedures that are not provided by TSP.

3.2. Preliminary unit root tests assuming structural constancy

The time series data are plotted as a thick line in Figs. 1–13. Though all the series seem to contain some structural changes, we at first assume that no structural changes exist at all, and conduct a t-value type ADF test. We adopt the difference-type AR(p) models expressed as Eq. (2.1) above, with a linear time trend γt, and Eq. (2.2) with a quadratic non-linear time trend κt^2. If there is neither drift nor trend, α, or γ and κ become zero.

$$\Delta y_t = \alpha + \gamma t + b_1 y_{t-1} + \sum_{i=2}^{p} b_i \, \Delta y_{t-i+1} + \varepsilon_t, \qquad \varepsilon_t \sim \text{i.i.d.}(0, \sigma_2) \tag{3.1}$$

$$\Delta y_t = \alpha + \gamma t + \kappa t^2 + b_1 y_{t-1} + \sum_{i=2}^{p} b_i \, \Delta y_{t-i+1} + \varepsilon_t, \qquad \varepsilon_t \sim \text{i.i.d.}(0, \sigma_2) \tag{3.2}$$

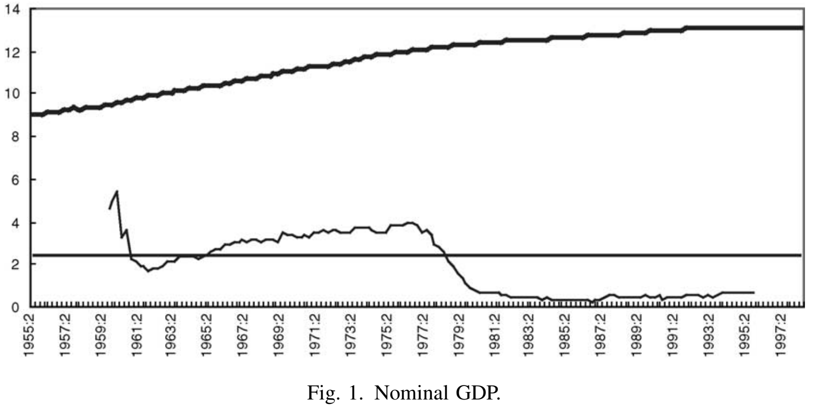

Fig. 1. Nominal GDP.

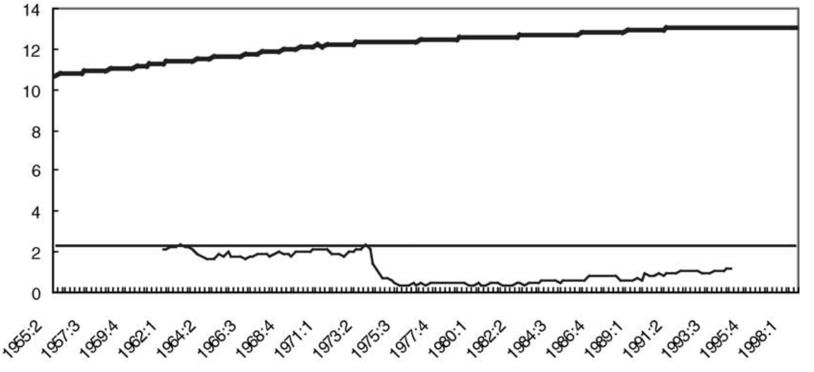

Fig. 2. Real GDP.

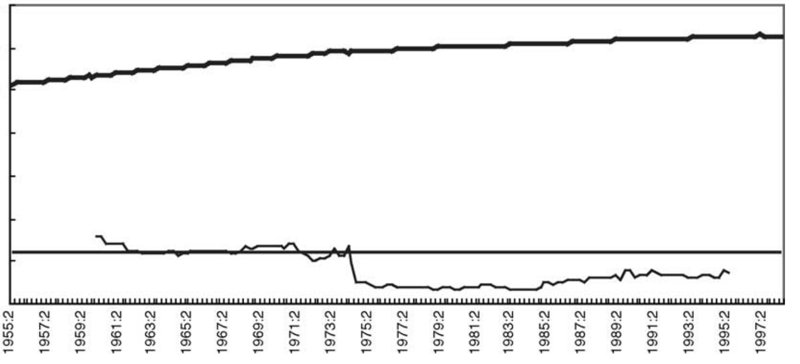

Fig. 3. Real private consumption.

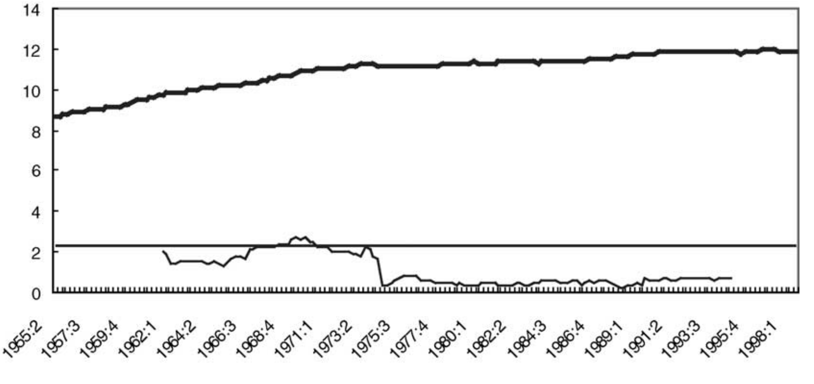

Fig. 4. Real private investment.

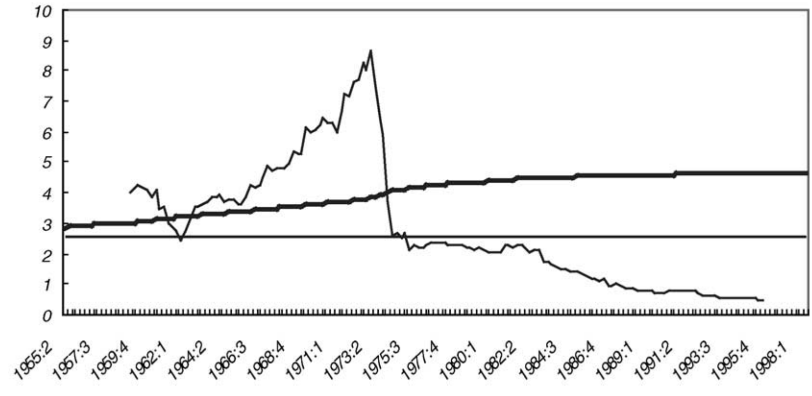

Fig. 5. GDP deflator.

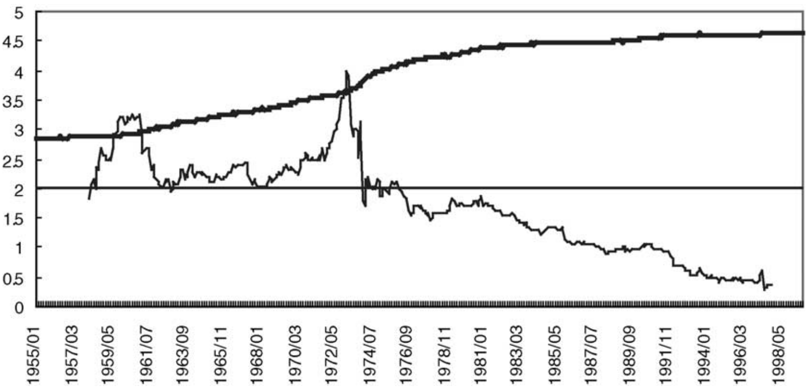

Fig. 6. Consumer price index.

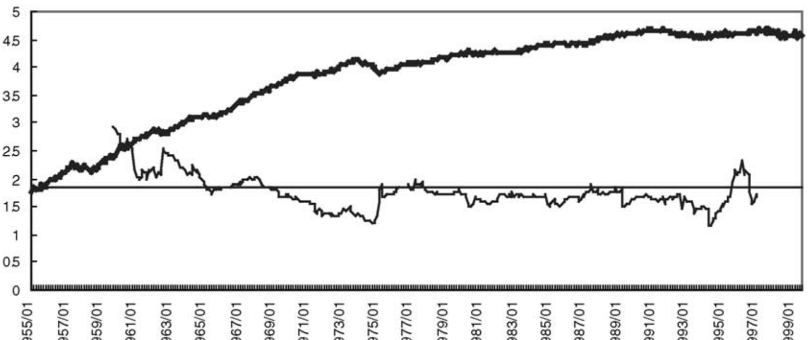

Fig. 7. Index of industrial production.

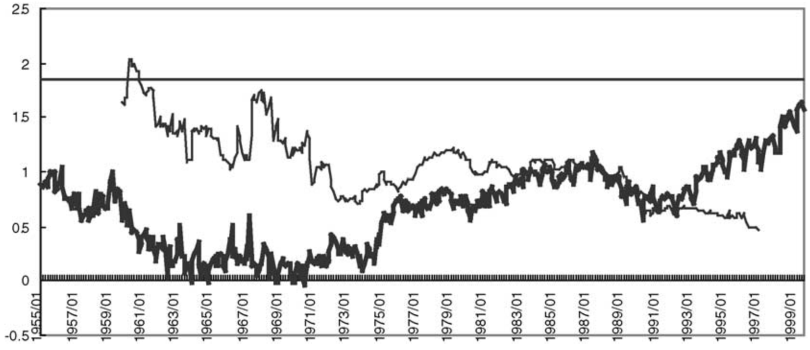

Fig. 8. Unemployment rate.

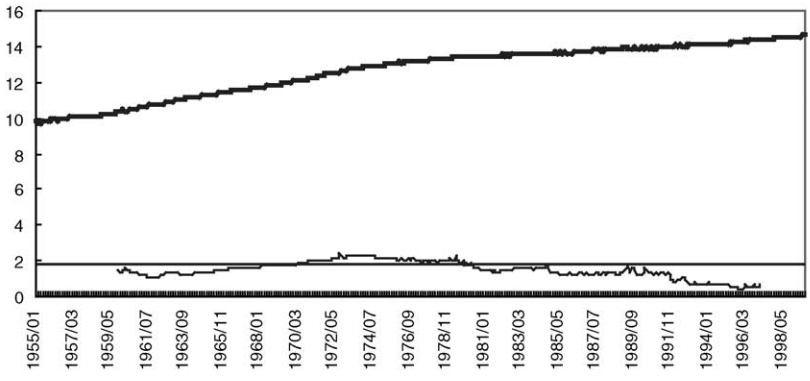

Fig. 9. M1.

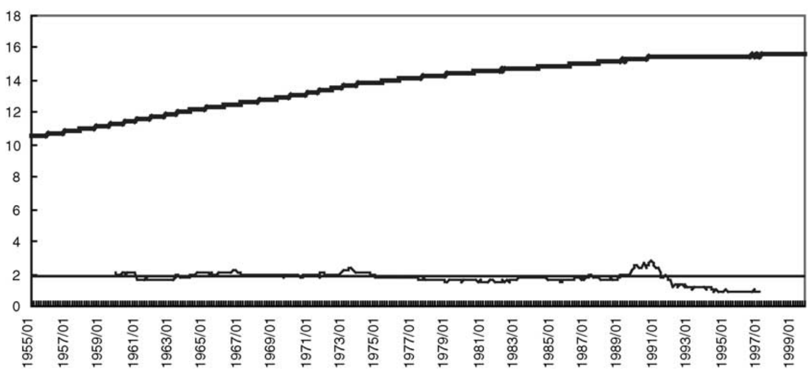

Fig. 10. M2 + CD.

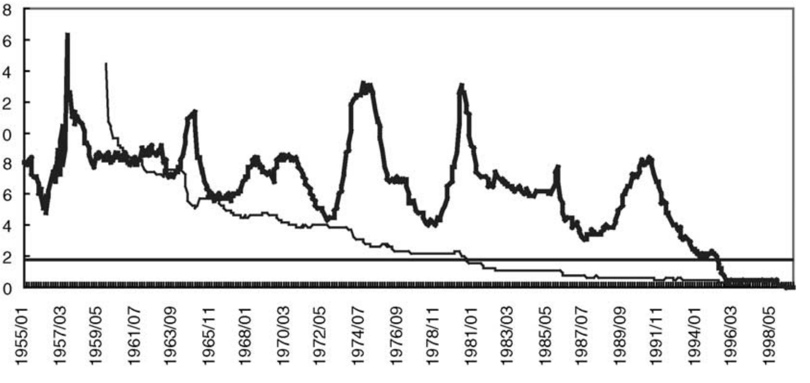

Fig. 11. Call rate.

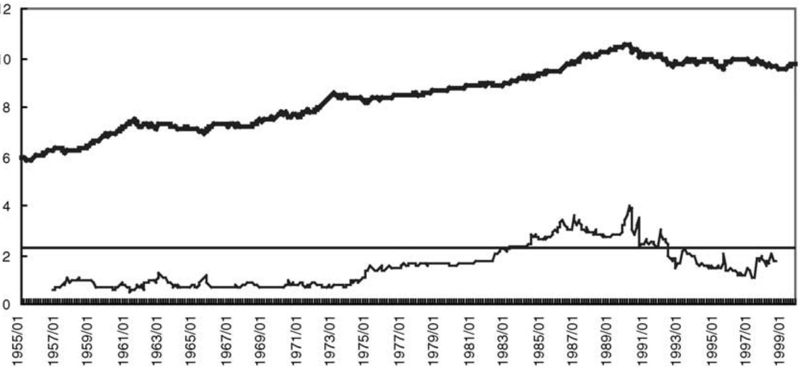

Fig. 12. Nikkei average stock price.

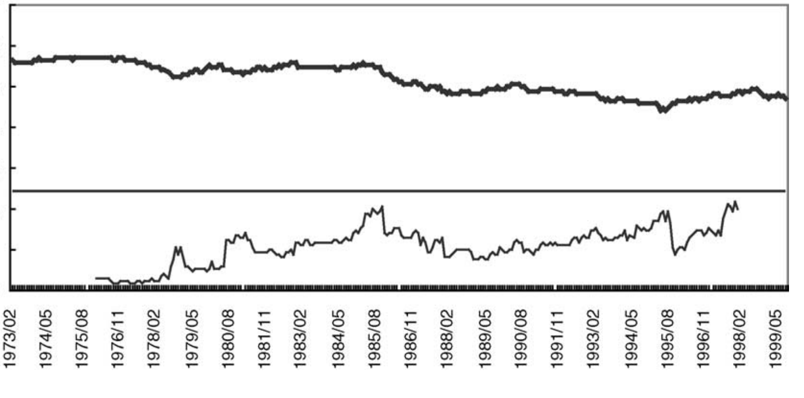

Fig. 13. Exchange rate.

For the same model, we conduct a more general PP test that does not impose the assumption of i.i.d. on the error term.

Since the time lag structure is different for each data series, it is desirable to estimate the optimal time lag by setting the maximum lag p_{MAX} as 2 years, although most previous Japanese research assumed a fixed time lag a priori. We estimate the optimal time lag p^* on the basis of Akaike Information Criteria (AIC) setting $p_{\mathrm{MAX}} = 8$ for quarterly data and $p_{\mathrm{MAX}} = 24$ for monthly data.

According to the results of preliminary ADF and PP tests shown in Table 1, the optimal time lags in the case of price variables, are 5 months for the exchange rate, 6 months for the Nikkei average stock price index, 9 months for the GDP deflator, 14 months for the Consumers Price Index, and 24 months for the original call rate. In the case of quantity variables, the optimal time lags are 1 year for nominal GDP, 1 year and a quarter for real private consumption, and 2 years for real GDP, real investment, the industrial production index, and the money supply.

In the case of the linear trend model (3-1), only the null hypothesis of a unit root for the call rate can be rejected at the 5% level by both the τ test based on Fuller (1976) and the P-value test. The Z_α-value and P-value of the PP test show that only the null hypothesis of a unit root for the call rate can be rejected at the 5% level by both of these tests.

In the case of the non-linear trend model (3-2), the null hypothesis is rejected at the 5% level by the P-value of the ADF test only for the call rate, nominal GDP, and $M2 + \mathrm{CD}$. The null hypothesis is rejected at the 5% level by the P-value of the PP test only for the call rate and the unemployment rate.

Miyakoshi and Tsukuda (1998) conducted ADF test for the same six time series as our study on the assumption of structural constancy in a linear trend model over a slightly shorter period than ours, and obtained the same result as ours that the null hypothesis of a unit root was rejected only in the case of the original call rate. However, their results differ from ours in that they did not adjust the call rate seasonally, did not add a trend term, and fixed the time lag as $p = 5$ for quarterly data and $p = 14$ for monthly data.[3]

Nelson and Plosser (1982) conducted ADF test for 14 US time series, among which 9 series are almost the same as ours, on the assumption of structural constancy in an AR(p) model with drift and time trend terms. They obtained the result that the null hypothesis of a unit root was not rejected in the case of the 13 time series, except for the unemployment rate.

Despite these differences, the results obtained are very similar to each other, and provide empirical support for the conclusion that the null hypothesis of a unit root is less likely to be rejected by the ADF and PP tests assuming structural constancy than by tests not making this assumption.

[3] Miyakoshi and Tsukuda (1998) conducted the Perron test, Zivot–Andrews test, Kunitomo test, and modified Chow–Yamamoto test, assuming structural breaks in the form of dummy variables to Japan's seven macroeconomic time series. They obtained the result that the Kunitomo test showed the highest testing power and it rejected a null hypothesis for unit root in all the series except the index of industrial production (IIP) and the Nikkei average stock price. However, their result seems implausible, since real GDP and IIP followed different stochastic process in their tests.

Table 1
Unit root tests assuming structural constancy

Time series	Lag p^*	ADF tests				PP tests	
		t-value	P-value	γ's t-value	κ's t-value	Z_α-value	P-value
Nominal GDP	4	1.6191	0.9999	−2.9397	−4.0245	1.4789	0.9997
	4	−3.4948	0.0420*	3.5537		−8.2218	0.8217
Real GDP	8	−0.9805	0.9652	−0.4862	−1.9302	−0.3422	0.9947
	8	−2.1336	0.5928	1.8349		−7.2197	0.8739
Real consumption	5	−0.9548	0.9499	−0.9421	−1.5327	−0.4796	0.9937
	5	−1.6291	0.9232	1.3835		−6.8399	0.8915
Real investment	8	−1.5346	0.8170	−0.0692	−1.0461	−2.4402	0.9575
	8	−1.6517	0.9186	1.0153		−5.1827	0.9515
GDP deflator	3	0.5100	0.9992	−1.1712	−3.1540	1.6252	0.9998
	3	−2.2704	0.5066	2.6311		−4.1353	0.9751
Consumer price index	14	−0.5978	0.9879	0.1614	−2.9523	0.9832	0.9993
	14	−2.5557	0.3306	2.8214		−5.1599	0.9522
Index of industrial production	24	−1.5451	0.8733	−1.0071	−1.0121	−2.2300	0.9640
	24	−1.4239	0.9044	0.8793		−20.9673	0.1704
Unemployment rate	24	−2.0604	0.6426	3.1924	0.2772	−15.9396*	0.1556
	24	−1.8856	0.7393	0.8127		−30.7768	0.0306*
M1	24	1.1687	0.9485	0.4011	−1.1655	−0.8461	0.9904
	24	−1.4799	0.8910	1.2156		−7.8534	0.8418
M2 + CD	24	0.5322	0.9994	−1.7269	−3.7265	0.8863	0.9991
	24	−3.5910	0.0303*	3.5224		−12.7642	0.5386
Call rate	24	−3.4690*	0.0428*	−3.0730	0.7230	−23.8347*	0.0323*
	24	−4.4170	0.0027*	1.4084		−31.4182	0.0271*
Call rate (logarithm)	18	1.9506	0.9999	−0.7493	−1.5804	10.8531	1.0000
	18	0.5093	0.9993	1.3155		4.7214	1.0000
Nikkei average stock price 225	6	−1.4532	0.8976	0.9231	−1.4167	−3.7163*	0.9026
	6	−1.9752	0.6920	1.6874		−7.1507	0.8772
Yen–Dollar exchange rate	5	−2.4151	0.4159	−2.1563	0.5890	−9.6725*	0.4585
	5	−2.4275	0.4081	−1.3316		−9.7270	0.7318

Note 1: The upper row of each series shows a linear time trend model, and the lower row shows a non-linear time trend model. *Note* 2: According to Fuller (1976), empirical distributions of τ-value for an AR(p) model with a constant and a linear time trend model are −4.40 at 1% significance level, −3.45 at 5% level, and −3.15 at 10% level when $T = 100$; −3.99 at 1% significance level, −3.43 at 5% level, and −3.13 at 10% level when $T = 250$; −3.98 at 1% significance level, −3.42 at 5% level, and −3.13 at 10% level when $T = 500$; −3.96 at 1% significance level, −3.41 at 5% level, and −3.12 at 10% level when $T = \infty$. The mark (*) denotes significance at 5% level.

3.3. Structural change tests and division of the estimation period

For the same 13 time series as above, we used the step-wise Chow-Yamamoto tests modified by Yamamoto (1996) to detect when and how many times structural changes

Table 2
Divided sub-periods

Nominal GDP	①1960:4–1976:3	②1976:4–1998:2	
Real GDP	①1962:4–1973:2	②1973:3–1998:2	
Real consumption	①1962:3–1971:1	②1971:2–1998:2	
Real investment	①1955:2–1969:2	②1969:3–1998:2	
GDP deflator	①1962:2–1973:1	②1973:2–1998:2	
CPI	①1962/10–1973/2	②1973/3–1999/8	
IIP	①1965/4–1977/3	②1977/4–1995/7	
Unemployment rate	①1960/10–1999/8		
M1	①1955/1–1979/5	②1979/6–1999/8	
M2 + CD	①1960/6–1973/5	②1973/6–1990/10	③1990/11–1999/8
Call rate	①1964/5–1995/6		
Nikkei stock price	①1955/1–1990/1	②1990/2–1999/8	
Yen–Dollar rate	①1973/2–1999/8		

occurred. Since test results are relatively more robust in the case of adding a linear time trend than in the case of adding a quadratic time trend as well, we use model (3-1) to conduct structural change tests. We assume structural changes for a drift α, a linear time trend γ, and all the coefficients b_i, using the estimated p^* as the optimal time lag on the assumption that it is constant over the whole period, though Yamamoto and Zhai (1995) did not estimate optimal time lags. We assume $\lambda = 1/4$ as in Yamamoto and Zhai (1995).

The thin curve in Figs. 1–13 shows estimated Chow's F statistics, and the thin line shows the critical F statistics at 1% significance level, respectively. If the former is greater than the latter, structural changes are significantly detected.

When Perron (1989), Zivot and Andrews (1992), Kunitomo (1996b) and Yamamoto and Zhai (1995) conducted unit root tests assuming a structural change, they assumed a priori that a structural change occurs only at one point in time. However, according to our structural change test, only real GDP experienced one break. The Yen–Dollar rate experienced no structural break, and all the other time series experienced successive structural changes over several periods.

In order to conduct unit root tests correctly, we exclude any unstable periods, if any, from the first or last of the sample periods, and divide the whole period into stable sub-periods at the point where a structural change is most noticeable. Table 2 shows the divided sub-periods.

3.4. Unit root tests assuming structural changes

We conduct the same t-value type ADF tests as we applied in the previous section in the divided periods during which structure is assumed to be relatively stable. We use Eq. (3.1) of an AR(p) model which has a drift α and a linear time trend γt. In cases where there is neither a drift nor a time trend, α or γ becomes zero. For the same model, we conduct a more general PP test that does not impose the assumption of i.i.d. on the error term.

We estimate the optimal time lag p^* on the basis of Akaike Information Criteria, setting $p_{\mathrm{MAX}} = 8$ for quarterly data and $p_{\mathrm{MAX}} = 24$ for monthly data.

If at least one of the ADF and PP tests rejects the null hypothesis of each time series in Table 3, we judge the series is trend stationary; otherwise we judge the series is

Table 3
Unit root tests assuming structural changes

Time series		Lag p^*	ADF tests		PP tests	
			t-value	P-value	Z_α-value	P-value
Nominal GDP	①	4	−3.9199*	0.0114*	−14.8627	0.1899
	②	7	0.6063	0.9970	−0.1999	0.9956
Real GDP	①	4	−1.9508	0.6280	−5.5410	0.7812
	②	6	0.1824	0.9957	1.2483	0.9996
Real consumption	①	5	−2.1485	0.5189	−9.7269	0.4548
	②	5	−0.9499	0.9505	−7.5375	0.6308
Real investment	①	2	−1.8127	0.6986	−6.5459	0.7015
	②	5	−1.7842	0.7124	−9.3576	0.4808
GDP deflator	①	2	−2.8854	0.1674	−28.4705	0.0121*
	②	4	−3.6253*	0.0278*	−7.6878	0.6087
CPI	①	6	−2.4248	0.3665	−22.3700	0.0437*
	②	14	−2.6921	0.2394	−7.6817	0.6092
IIP	①	24	−0.0461	0.9937	−1.7799	0.9754
	②	18	−1.2598	0.8975	−16.6003	0.1373
Unemployment rate	①	24	−1.9353	0.6362	−46.5938	0.0002**
M1	①	24	−3.3393+	0.0600+	−10.3883	0.4106
	②	17	−0.9077	0.9553	−49.4751	0.0001**
M2 + CD	①	24	−2.4220	0.3680	−6.4207	0.7117
	②	16	−3.0143	0.1281	−5.5595	0.7798
	③	17	−2.2012	0.4892	−28.4731	0.0121*
Call rate	①	8	−4.1794*	0.0048**	−16.4668	0.1408
Nikkei average stock price 225	①	5	−1.8897	0.6600	−6.3498	0.7174
	②	6	−2.6798	0.2446	−15.0319	0.1845
Yen–Dollar rate	①	5	−2.3781	0.3913	−9.6725	0.4585

Note 1: ①, ② and ③ denote divided sub-period in Table 2. *Note* 2: According to Fuller (1976), empirical distributions of τ-value for an AR(p) model with a constant and a linear time trend model are −4.40 at 1% significance level, −3.45 at 5% level, and −3.15 at 10% level when $T = 100$; −3.99 at 1% significance level, −3.43 at 5% level, and −3.13 at 10% level when $T = 250$; −3.98 at 1% significance level, −3.42 at 5% level, and −3.13 at 10% level when $T = 500$; −3.96 at 1% significance level, −3.41 at 5% level, and −3.12 at 10% level when $T = \infty$. The marks (**), (*), and ($^{+}$) denote significance at 1, 5, and 10% level, respectively.

difference stationary (unit root process). The results of these judgments are shown in Table 4.

According to the results in Table 4, the patterns of structural change are classified into six categories: trend stationary series with selected stable period (unemployment rate, call rate); trend stationary series before and after structural break (GDP deflator, M1); series which changed from trend stationary to difference stationary (nominal GDP); series which changed from difference stationary to trend stationary (CPI, M2 + CD); difference stationary series with no structural break (Yen–Dollar rate); and difference stationary

Table 4
Results of judgments on unit root tests

Time series	Period ①	Break	Period ②	Break	Period ③
Nominal GDP	TS	1976:3	DS		
Real GDP	DS	1973:2	DS		
Real consumption	DS	1971:1	DS		
Real investment	DS	1969:2	DS		
GDP deflator	TS	1973:1	DS		
CPI	DS	1973/2	DS		
IIP	DS	1977/3	DS		
Unemployment rate	TS				
M1	TS	1979/5	TS		
M2 + CD	DS	1973/5	DS	1990/10	TS
Call rate	TS				
Nikkei stock price	DS	1990/1	DS		
Yen–Dollar rate	DS				

*Note*1: TS and DS mean trend stationary and difference stationary, respectively.

series before and after a structural break (real GDP, real consumption, real investment, IIP, Nikkei average stock price 225).

In the case of unit root tests assuming structural changes, the number of series for which the null hypothesis of a unit root is rejected exceeded the number assuming structural constancy. This empirical fact affirmatively supports the theorem by Perron (1989) and Kunitomo (1996a) that a unit root test, which ignores structural change when it exists, can not reject the null hypothesis of a unit root.

As for real quantity variables, all the data of real GDP, index of industrial production, real consumption and real investment are difference stationary before and after a structural break. This empirical fact affirmatively supports the real business cycle theory of Kydland and Prescott (1982) and Long and Plosser (1983). Takeuchi (1992) obtained the result that real GDP was difference stationary before and after a structural break, but on the contrary the index of industrial production was trend stationary before and after a structural break. Yamamoto and Zhai (1995) obtained the result that real GDP was difference stationary before a structural break, but on the contrary the index of industrial production was trend stationary before a structural break. Their results are implausible, since these series are typical variables for representing the real economy, are often used as substitutes, and hence are likely to follow a similar stochastic process. Some researchers judge whether real business cycle theory is verified or not by using a unit root test for real GDP alone, but this is dangerous. It seems to be necessary to test not only real GDP but also the related real variables in order to judge this issue correctly.

As for nominal variables, the GDP deflator and consumer price index are trend stationary except for the consumer price index during period ①. Nominal GDP is trend stationary in period ① and difference stationary in period ②. Since nominal GDP is real GDP times the GDP deflator, it should follow a stochastic process which is composed of those of the real GDP and the GDP deflator. Therefore the result seems to be plausible.

The absolute unemployment rate has no significant break, and is trend stationary except for the initial sample period.

As for monetary aggregates, M1 is trend stationary before and after a structural break, and M2 + CD is difference stationary in periods ① and ② but is trend stationary in period ③. The call rate, the most representative interest rate for short-term money markets, is trend stationary throughout the sample period. It follows a stochastic process more similar to that of M1 than that of M2 + CD, implying a closer relationship with M1 than M2 + CD. On the contrary, the consumer price index follows a stochastic process more similar to that of M2 + CD than that of M1, implying a closer relationship with M2 + CD than M1. These results are empirically plausible. Yamamoto and Zhai (1995) obtained the result that the process of M1 changed from difference stationary before a structural break to trend stationary after it, but on the contrary the call rate changed in the opposite way. Their result seems to be implausible.

The Nikkei average stock price 225 is difference stationary before and after a structural break. Takeuchi (1992) obtained a similar result that it is difference stationary throughout the sample period. The Yen–Dollar exchange rate has no significant structural break and is difference stationary. Kunitomo (1996b) obtained a similar result on the basis of daily data that it is difference stationary throughout the sample period, whether a break in trend is assumed or not.

4. Concluding remarks

We tested the null hypothesis of a unit root for thirteen major macroeconomic time series in Japan in both cases of structural constancy and structural change. Structural changes are assumed to contain not only changes in the parameters of the drift term and time trend, but also changes in all the parameters of time lag structure. They are also assumed to be either temporal or continuous, and to occur multiple times. In order to detect such structural changes endogenously we adopted an augmented step-wise Chow test modified by Yamamoto (1996).

Following Yamamoto and Zhai (1995), we applied Yamamoto (1996) method in slightly different ways, and we obtained results which are different from each other even concerning our common data series. There are several reasons for this. The first reason is the difference in the sample period of the data set: they set a sample period from 1955 to 1965 to 1992, while we set it from 1955 to 1998 to 1999. The second reason is the difference in the optimum time lag: a priori they set $p^* = 7$ for quarterly data and $p^* = 14$ for monthly data, but we estimated p^* with the aid of AIC. Setting the optimum time lag arbitrarily tends to distort estimation results, and therefore it is desirable to estimate it with the aid of some information criteria. The third reason is the differences in estimating points of structural change, and in dividing estimation periods. They considered only a temporal break, but it is desirable to take into account both temporal and continuous changes. The fourth reason is that we utilized the PP test as well as the ADF test. Any testing method for unit root has both merits and demerits, and has not necessarily critical testing power, and hence it is desirable to apply multiple testing methods.

Structural changes were significantly detected for all the time series except the Yen–Dollar exchange rate. The null hypothesis of unit root was rejected for seven time series in some time period. But it was not rejected for the main real time series such as real GDP, real private consumption, real total investment, and the industrial production index, implying robust evidence for a real business cycle. It was rejected for neither the Nikkei average stock price index nor the Yen–Dollar exchange rate, which are usually supposed to follow a typical random walk process. The null hypothesis of unit root was rejected in more cases when structural changes were assumed to exist than when a structural change was assumed not to exist. This result supports affirmatively Perron's (1989) theorem that a unit root test which ignores a structural change when it exists, does not reject the null hypothesis of unit root even if the true model is trend stationary. Some trend stationary series change to difference stationary or vice versa after a structural break, and thus the Perron-type approach to integrate a structural change test and a unit root test fails to capture true changes, implying that it is better to utilize Yamamoto (1996) method than the Perron-type approach.

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Appendix A. Yamamoto's (1996) Step-wise Chow test

Following Yamamoto (1996), consider a Wald test for linear restrictions in a multivariate time series model. An n-variate stochastic process $\{X_t = [x_{it}]\}$ is expressed as follows.

$$X_t = \delta_0 + \delta_1 t + \omega_t \tag{A.1}$$

where $\delta_0 = [\delta_{i0}]$ and $\delta_1 = [\delta_{i1}]$ are a coefficient vector, and $\{\omega_t = [\omega_{it}]\}$ is a pth order autoregressive process.

$$\omega_t = \sum_{k=1}^{p} A_k \omega_{t-k} + \eta_t \tag{A.2}$$

where A_k is a coefficient matrix, η_t is an i.i.d. random disturbance with zero mean, its covariance matrix being $\Sigma = [\sigma_{ij}]$. The order p is known. $A(z) = I_n - \sum_{k=1}^{p} A_k \omega z^k = 0$ is assumed to lie on a unit circle or external to it.

Substituting $\omega_t = X_t - \delta_0 - \delta_1 t$ into the above equation, we obtain

$$X_t = \sum_{t=1}^{p} A_t X_{t-k} + \gamma_0 + \gamma_1 t + \eta_t \tag{A.3}$$

where $\gamma_0 = [\gamma_{i0}] = A(1)\delta_0 - A'(1)\delta_1$, $\gamma_1 = [\gamma_{i1}] = A(1)\delta_1$.

This is expressed as follows:

$$X_t = A_k^{+\prime} Y_{t-1}^{+} + \eta_t, \qquad A_k^{+\prime} = [A_1, A_2, \cdots, A_p, \gamma_0, \gamma_1] = [\beta_i^{+\prime}],$$
$$Y_{t-1}^{+} = [X_{t-1}{}', X_{t-2}{}', \cdots, X_{t-p}{}', 1, t]' \tag{A.4}$$

These are rewritten as follows:

$$X = Y_{-1}^{+} A^{+} + \eta, \qquad X = [X_{p+1}, X_{p+2}, \cdots, X_T]',$$
$$Y_{t-1}^{+} = [Y_p^1, Y_{p+1}^{+}, \cdots, Y_{T-1}^{+}]', \qquad \eta = [\eta_{p+1}, \eta_{p+2}, \cdots, \eta_T]' \tag{A.5}$$

or as follows in the form of a single equation:

$$s = [I_n \otimes Y_{-1}^{+}]\, \beta^{+} + u \tag{A.6}$$

where $s = \mathrm{Vec}(X)$, $\beta^{+} = \mathrm{Vec}(A^{+})$, $u = \mathrm{Vec}(\eta)$. Vec $(\cdot)$ denotes column operator, and $\otimes$ denotes Kronecker product.

Let us consider the following hypothesis test.

$$H_0 : R^{+}\beta^{+} = r, \qquad H_1 : R^{+}\beta^{+} \neq r \tag{A.7}$$

where R^{+} is an $m \times 2n(np+2)$ matrix of restriction equations with rank $(R^{+}) = m \cdot r$ is an $(m \times 1)$ vector.

Adding certain normal random variables to Eq. (A.3) gives the following modified equation.

$$X_t = \sum_{t=1}^{p} A_t X_{t-k} + \gamma_0 + \gamma_1 t + \sum_{t=1}^{p} A_k^{*} X_{t-k}^{*} + \gamma_0^{*} 1^{*} + \gamma_1^{*} t^{*} + \eta_t,$$
$$X_{t-k}^{*} = X_{t-k} + T^{-\lambda}\varepsilon_{kt} \quad (k = 1, 2, \cdots, p), \qquad 1^{*} = 1 + T^{-\lambda}\varepsilon_{0t}$$
$$t^{*} = t + T^{-\lambda}\varepsilon_{p+1t} \tag{A.8}$$

where ε_t and ε_{p+1t} are scalar random variables, $\varepsilon_{kt} = [\varepsilon_{kjt}]$ ($k = 1, 2, \ldots, p$) is an $(n \times 1)$ vector of i.i.d. random variables, with mean zero, variance $\Omega^k = \mathrm{diag}\,\{\Omega_{ij}^k\}$ that satisfies $|\varepsilon_{0t}|^{2+\delta} < \infty$, $|\varepsilon_{p+1t}|^{2+\delta} < \infty$, $|\varepsilon_{kjt}|^{2+\delta} < \infty$, for some δ (>0) $0 < \lambda < 1/2$.

Yamamoto (1996) proved that a Wald test statistic of this modified model testing for the hypothesis (A.7) converges asymptotically to a χ^2 distribution. Therefore, we can specify the model to be tested actually.

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