E c o n o m i c s B u l l e t i n

Optimal control theory for inflation targeting

Thiago Veloso
National Agency for Electric Energy

Roberto Meurer
Department of Economics, Federal University of Santa Catarina

Sergio Da Silva
Department of Economics, Federal University of Santa Catarina

Abstract

We make a case for the usefulness of an optimal control approach for the central banks' choice of interest rates in inflation target regimes. We illustrate it with data from selected developed and emerging countries with longest experience of inflation targeting.

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l. Introduction

Inflation targeting is now a new gold standard for central banks. The regime is believed to perform better than, for instance, the alternative of controlling money for clamping down on inflation by giving monetary policy more transparency and thus credibility (Svensson 1997, Mishkin and Schmidt-Hebbel 2007). Instead of trying to meet monetary targets, central banks use their own money to determine short-term interest rates and thus control inflation directly. Tethering inflationary expectations is vital under this regime. If agents believe that the inflation target will be hit, then inflationary shocks will be absorbed.

The 1990s were favorable to low inflation regardless of inflation targeting (Masson *et al.* 1997). And the case for inflation targeting is not that straightforward for emerging market countries. This is so because of their fragile institutions (Eichengreen 2002, Calvo and Reinhart 2000, Mishkin 2004), excess liabilities in foreign currency, and high degree of passthrough (Eichengreen 2002). Exchange rate depreciation size also matters in such countries (Eichengreen 2002) in that it might cause a nonlinear impact on output, as in Aghion *et al.* (1999) and Krugman (2003). Yet by 2005 eight developed markets and thirteen emerging countries had adopted inflation targeting; coincidentally or not, inflation was tamed in such countries (Mishkin and Schmidt-Hebbel 2007).

Another appeal of inflation targeting is its consistency with the Taylor rule and thus its supposed advantage over a fixed exchange rate anchor to monetary policy (Eichengreen 2002, Masson *et al.* 1997). Yet mixing inflation targeting with flexible exchange rates is not always feasible (Calvo and Reinhart 2000). Inflation targeting has also been linked to a more favorable inflation-unemployment tradeoff (Clifton *et al.* 2001, Clarida *et al.* 1999). But the regime can also create more nominal rigidity and thus worsen the inflation-unemployment tradeoff in the presence of low inflation and longer-term contracts (Posen 1998, Hutchison and Walsh 1998).

This paper will make a case for the usefulness of optimal control analysis for the central banks' choice of interest rates in inflation target regimes. We will employ a central bank reaction function considering the Taylor rule within a framework of optimal control (Chow 1975). The model will select the inflation-targeting interest rate as a solution to the minimization of the central bank's loss function subject to the behavior of output, inflation, and exchange rate changes.

The rest of the paper is organized as follows. Section 2 will present our model. Section 3 will show data. Section 4 will perform analysis. And section 5 will conclude.

2. Theoretical model

Now we present an optimal control model that builds on the Taylor rule model of Eichengreen (2002). Eichengreen's model tracks the major features of open emerging markets, and can be described by equations (1)–(3).

$$\pi_t^* = \pi_t + \beta_1(Y_t - \overline{Y}) + \beta_2(e_t - e_{t-1}) + \varepsilon_{t+1} \tag{1}$$

$$Y_{t+1} - \overline{Y} = \alpha_1(Y_t - \overline{Y}) - \alpha_2(i_t - i_t') + \alpha_3 e_t + \eta_{t+1} \tag{2}$$

$$E(e_{t+1}) - e_t = i - i_t^* + v_t , \tag{3}$$

where π and π^* are inflation rate and inflation rate target respectively, $Y - \overline{Y}$ is output deviation from its natural level, e is the nominal exchange rate (dollar price of a country's currency), i, i^*, and i' are domestic, foreign, and neutral interest rate respectively, ε and η are disturbance terms, and ν is a financial disturbance (Calvo's shock).

Equation (1) is the expectational Phillips curve, and equation (2) is the aggregate demand for an open economy. The interest rate impact on output is captured by parameter α_2 (and indirectly through α_3). Equation (3) is uncovered interest parity, where $E(e_{t+1})$ is assumed to be constant when deriving the Taylor rule.

High degree of passthrough is tracked by both a big β_2 and a small α_3 because these values mean that exchange rate depreciation causes rapid increase in domestic and tradable prices, decreased competitiveness, and then low effect on output. Excess liabilities in foreign currency can also be represented by a small α_3. If α_3 is small (and positive) the central bank has less fear of floating. Yet a big depreciation means a negative α_3, and this increases the fear of floating.

Our optimal control approach to inflation targeting can be extended to other formulations of the Phillips curve and aggregate demand by changing the assumptions about the forward or backward looking features of the model, as discussed by e.g. Maria-Dolores and Vazquez (2006).

The solution to the model above is an interest rate reaction function. We suggest that such a reaction function will result from the minimization of the central bank's loss function. We arbitrarily choose to minimize the loss function (4) over ten periods subject to a system of equations representing the behavior of output, inflation, and exchange rate changes, i.e.

$$E_0 W = E_0 \sum_{t=1}^{10} \mu_{1,t} (Y_t - Y_t^*)^2 + \mu_{2,t} (\pi_t - \pi_t^*)^2 \tag{4}$$

s.t.

$$Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \alpha_2 i_t + \varepsilon_t \tag{5}$$

$$\pi_t = \beta_0 + \beta_1 \pi_{t-1} + \beta_2 (e_t - e_{t-1}) + \beta_3 Y_t + \eta_t \tag{6}$$

$$e_t - e_{t-1} = \gamma_0 + \gamma_1 (e_{t-1} - e_{t-2}) + \nu_t \, , \tag{7}$$

where $E_0 W$ is the loss function (given the values of output, inflation, and exchange rate changes at $t = 0$), and $\mu_{1,t}$ and $\mu_{2,t}$ are the costs of not reaching the desired output level Y_t^* and the inflation target respectively. Equations (5)–(7) are similar to Eichengreen model (equations (1)–(3)). The differences are as follows. Equation (5) shows output path as a function of the interest rate. Both equations (5) and (6) are quite standard (e.g. Svensson 1997) but consider desired output rather than the deviation from natural output (Romer 2001). It is preferable to use output rather than output gap because of the difficulty involved in finding a statistically significant coefficient for the relation output gap-inflation in quarterly models (Gali and Gertler 1999). Equation (7) comes from uncovered interest parity and a first-difference autoregressive model (Muinhos *et al.* 2002). By rewriting $E_t(e_{t+1}) - e_t = \delta_0 + \delta_1(i_t - i_t^f) + u_t$ in first differences and considering $\Delta\left[E_t(e_{t+1})\right] = E_t\Delta e_{t+1}$ one gets $E_t\Delta e_{t+1} - \Delta e_t = \delta_1\Delta(i_t - i_t^f)$. Inserting the rule for expectations formation $E_t\Delta e_{t+1} = \gamma_1\Delta e_{t-1} + \gamma_2(\pi_{t-1} - \pi_{t-1}^f)$ into the first-difference equation produces $\Delta e_t = \gamma_1\Delta e_{t-1} - \delta_1\Delta(i_t - i_t^f) + \gamma_2(\pi_{t-1} - \pi_{t-1}^f) + \varepsilon_t^*$. The latter can then be further simplified to generate equation (7).

Note that expectations play a role in monitoring inflation and this can affect the model's reduced-form coefficients, i.e. the model is subject to the Lucas critique. A more rigorous approach would be to firstly estimate the structural parameters associated with a new Keynesian-type, open economy model (as in Del Negro *et al.* (2005) and Maria-Dolores and Vazquez (2006)), and then solve the optimal control problem faced by the central bank subject to the restrictions imposed by the model. However, for our purposes in here it suffices to take a nonstructural model.

The solution to the problem is the interest rate reaction function (8), i.e.

$$\left[i_t\right] = G_t \begin{bmatrix} Y_{t-1} \\ \pi_{t-1} \\ \Delta e_{t-1} \\ i_{t-1} \end{bmatrix} + g_t, \tag{8}$$

where $G_t = \left[\theta_{1,t}\ \ \theta_{2,t}\ \ \theta_{3,t}\ \ \theta_{4,t}\right]$. Reaction functions for each of the ten periods obtain after reckoning $G_{10}, G_9, ..., G_1$ and $g_{10}, g_9, ..., g_1$ by differentiating the Lagrangean

$$L_1 = \tfrac{1}{2}\sum_{t=1}^{10}(y_t - a_t)'K_t(y_t - a_t) - \sum_{t=1}^{10}\lambda_t'(y_t - Ay_{t-1} - Cx_t - b), \tag{9}$$

where

$$y_t = \begin{bmatrix} Y_t \\ \pi_t \\ \Delta e_t \\ i_t \end{bmatrix}, K_t = \begin{bmatrix} \mu_{1,t} & 0 & 0 & 0 \\ 0 & \mu_{2,t} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, a_t = \begin{bmatrix} Y_t^* \\ \pi_t^* \\ \Delta e_t^* \\ i_t^* \end{bmatrix}, x_t = \left[i_t\right]. \tag{10}$$

Matrices A and C, and vector b are the parameters of equations (5), (6), and (7) in their reduced form, and are assumed to be constant. Equation (9) refers to the minimization of loss function $W = \tfrac{1}{2}\sum(y_t - a_t)'K_t(y_t - a_t)$ subject to equations (5), (6), and (7) rewritten as a first-order difference equation system, i.e. $y_t = Ay_{t-1} + Cx_t + b$. And W is loss function (4) in matrix notation for K_t and a_t.

By differentiating (9) with respect to x_t, y_t, and λ_t, and considering only the deterministic part of (5), (6), and (7), one can get $G_{10}, G_9, ..., G_1$ and $g_{10}, g_9, ..., g_1$ using (Chow 1975)

$$G_t = -(C'H_tC)^{-1}C'H_tA \tag{11}$$

and

$$g_t = -(C'H_tC)^{-1}C'(H_tb - h_t)\,, \tag{12}$$

where $H_t = K_t$ and $h_t = K_t a_t$ for $t = 10$. One advantage for a central bank to employ reaction function (8) is that it can choose the best interest rate by considering its effects in several subsequent periods. Another advantage of the optimal control approach is to allow one to calibrate the theoretical model with econometric estimates of the parameters in A, C, and b.

3. Data

We considered a sample of developed and emerging countries with longest experience of inflation targeting. They are the United Kingdom (UK), Canada (CAN), New Zealand (NZL), and Sweden (SWE). The emerging countries are Chile (CHI), Poland (POL), Czech Republic (CZE), and Korea (KOR). The quarterly data for the variables in equations (5)–(7) as well as i_t were taken from the IMF's International Financial Statistics. The data range is from 1990–Q1 to 2005–Q1. Our aim is to estimate such equations and parameters, and then get the interest rate reaction function.

We considered real GDP to represent output. We used the GDP implicit price deflator and made $2000\text{:Q}1 = 1$ in order to get real GDP from nominal GDP. For inflation we took changes in the producer price index, apart from Chile (where the consumer price index was taken). For exchange rate changes we considered the closing quotes. For interest rate we considered the money market rate, apart from the UK, Sweden, and Chile. For the UK and Sweden we took the government bond yield, and for Chile we considered the discount rate.

4. Analysis

Tables 1–3 show the estimates for equations (5)–(7) using ordinary least squares. (There are other estimation techniques, such as a Bayesian approach; this has been employed, for instance, in a dynamic stochastic general equilibrium framework by Del Negro *et al.* 2005.) Our estimation choice can be justified on the basis that there is no interdependence between the endogenous variables; put another way, each equation presents a one-way causal relationship. Disturbances ε_t, η_t, and ν_t were found contemporaneously unrelated. We also checked for autocorrelation in residuals employing Breusch-Godfrey's LM test. The presence of autocorrelation was corrected by Cochrane-Orcutt estimation.

Coefficient α_3 is absent from Table 1, i.e. exchange rate changes were not statistically significant. The output response to i_t was stronger for the UK, Sweden, and Poland. And the coefficient values in Tables 1–3 show that it makes no difference whether a country is developed or not. The coefficient of passthrough (i.e. that of π_{t-1}) is higher for the emerging countries (Table 2), but even for this set of countries the values vary a great deal.

Table 4 and 5 show the central banks' reaction functions reckoned by Chow (1975) methodology. The coefficients of matrix G_t were quite similar for the ten periods, and then we display those for two periods only. The values of G_t were not influenced by either output target, inflation target, or the initial conditions. To calculate matrices $g_{10}, g_9, ..., g_1$ we set both output and inflation target at 0.5 percent per quarter (~ 2 percent a year); this figure is based on the rationale presented in Fischer (1996). For the initial conditions we took the endogenous variables' values at 2005:Q1. We also assumed that the central banks do not change the penalties for output and inflation deviation from the target, which means assuming $\mu_{1,t}$ and $\mu_{2,t}$ constant for the ten quarters. The F test in Table 4 shows that the countries are similar regarding the sensibility of the optimal interest rate to inflation and exchange rate. The observed F is less than the tabulated value of 5.99 (5 percent significant). The results in Table 4 also depend critically on α_2.

Having found the reaction functions, we then applied optimal control analysis (and loss function (4)) to get the paths of output and inflation deviation. The paths allow one to assess the performance of a country regarding the chosen target. Chow methodology suggests decomposing (4) into one deterministic and one stochastic part. For convenience, here we consider the deterministic part only. The deterministic loss function can be found by rewriting (4) as

$$W = \sum_{t=1}^{10} \mu_{1,t} (\overline{Y}_t - Y_t^*)^2 + \mu_{2,t} (\overline{\pi}_{tt} - \pi_t^*)^2 , \tag{4'}$$

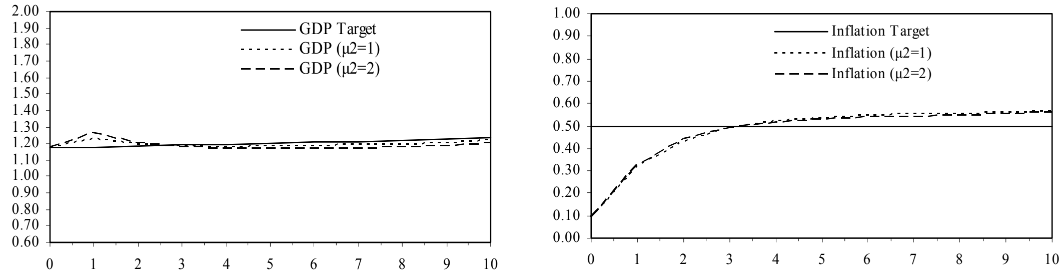
where $\overline{Y}_t$ and $\overline{\pi}_t$ are meant that we dropped ε_t and η_t from (1) and (2). Table 5 shows the total of deviations for the initial conditions $\overline{Y}_0 = Y_0$, $\overline{\pi}_0 = \pi_0$, and $\Delta\overline{e}_0 = \Delta e_0$. The emerging countries were found to deviate more from the target. (Figures 1 and 2 show the paths for output and inflation after optimization at $t = 1$.)

The targets were not hit in Figures 1 and 2 because we neglected the stochastic part in the loss function. Targets are only hit when the number of variables in the loss function matches the number of instrumental variables. This cannot occur in our model of two variables (output and inflation) and only one instrumental variable (interest rate). Calibrating the inflation weight in the loss function (i.e. making $\mu_{2,t} = 2$) shows that the countries can approach more closely the inflation target at the expense of the output target.

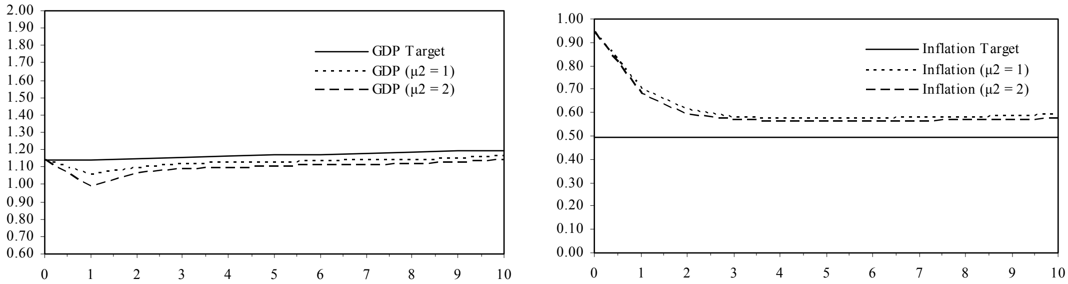
5. Conclusion

This paper straightforwardly shows how an optimal control analysis can be employed by central banks in their choice of interest rates under inflation target regimes. Data from selected developed and emerging countries with longest experience of inflation targeting were taken to illustrate. We incidentally found that the emerging countries deviate more from the target after optimization.

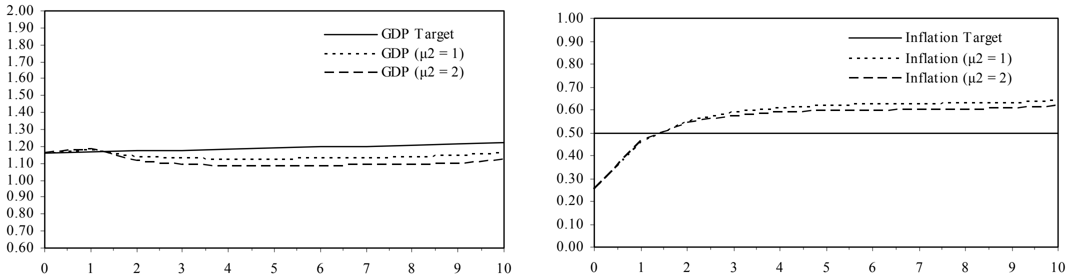
UK



CAN



NZL



SWE

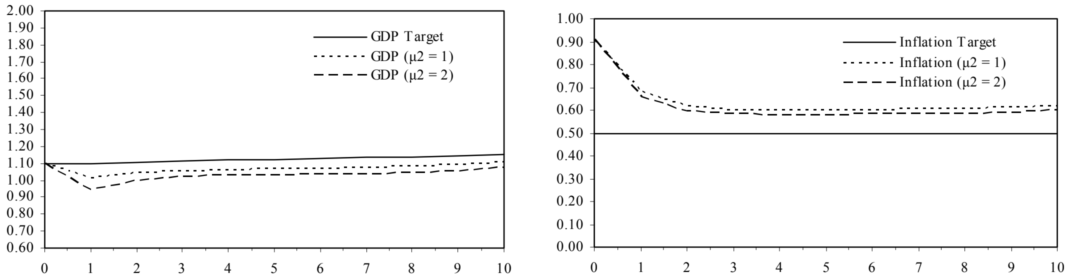


Figure 1. Developed countries' optimal path for GDP and inflation

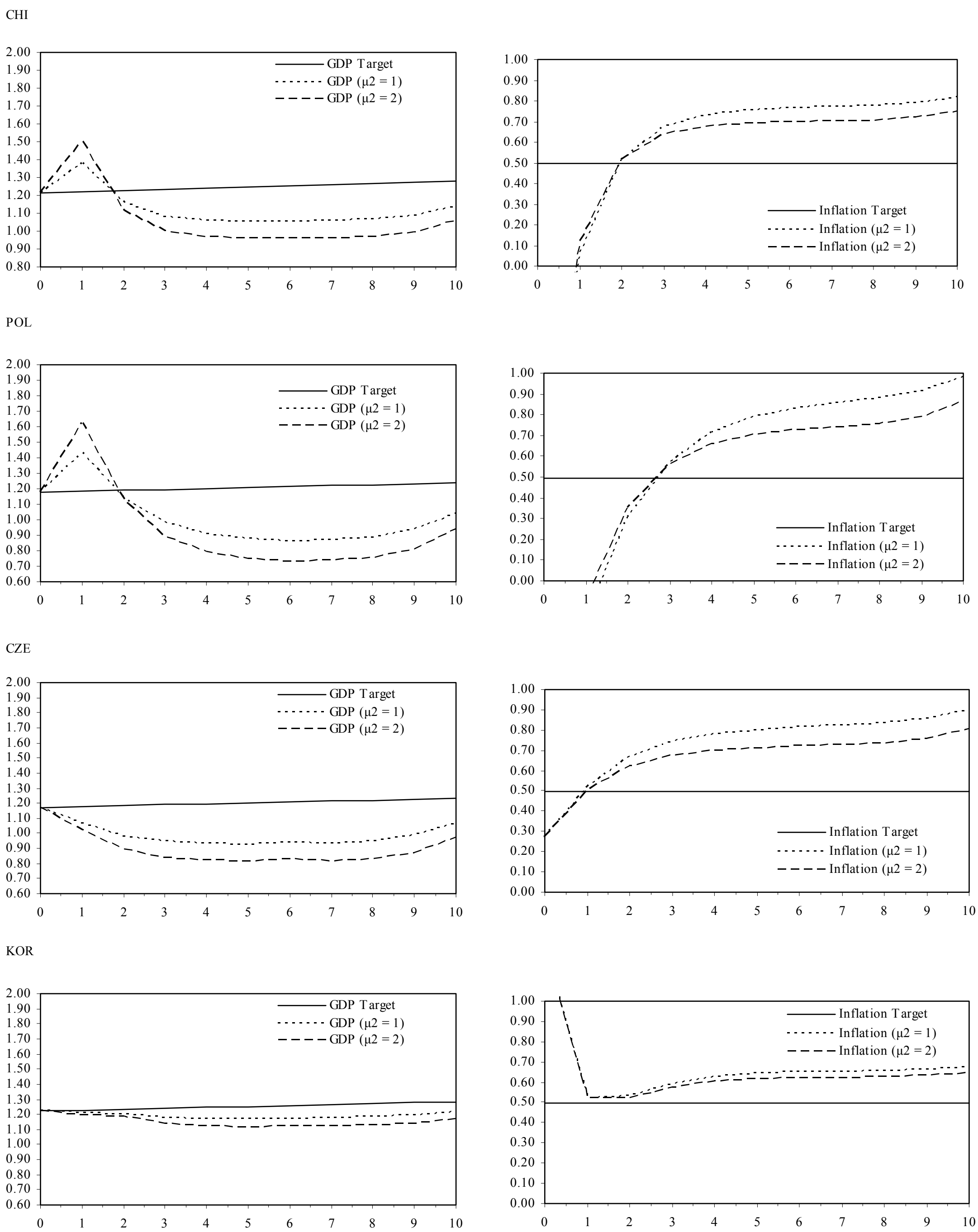


Figure 2. Emerging countries' optimal path for GDP and inflation

Table 1. GDP behavior (equation (5))

Dependent variable: Y_t								
	Coefficient (t-statistic)							
	UK	CAN	NZL	SWE	CHI	POL	CZE	KOR
	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1996:Q1–2005:Q1	1994:Q4–2005:Q1	1994:Q1–2005:Q1	1990:Q1–2005:Q1
Intercept	0.317**	0.019*	0.021*	0.695***	0.136*	0.724***	0.261***	0.204***
	(2.622)	(1.719)	(1.728)	(4.918)	(1.737)	(4.053)	(2.829)	(3.178)
Y_{t-1}	0.751***	0.994***	0.997***	0.408***	0.894***	0.425***	0.772***	0.854***
	(7.844)	(98.686)	(94.451)	(3.398)	(12.927)	(3.011)	(9.379)	(17.107)
i_t	–1.171**	–0.155**	–0.175***	–1.959***	–0.285**	–1.060***	–0.208*	–0.571***
	(–2.189)	(–2.818)	(–2.912)	(–3.951)	(–2.059)	(–3.030)	(–1.694)	(–2.766)
R squared	0.833	0.996	0.995	0.995	0.957	0.689	0.821	0.948
Adjusted R	0.827	0.996	0.995	0.995	0.954	0.671	0.812	0.946
LM test								
1 lag	$p = 0.901$	$p = 0.807$	$p = 0.265$	$p = 0.097$	$p = 0.775$	$p = 0.035$	$p = 0.592$	$p = 0.037$
2 lags	$p = 0.000$	$p = 0.939$	$p = 0.513$	$p = 0.001$	$p = 0.300$	$p = 0.067$	$p = 0.0001$	$p = 0.005$
ARCH								
1 lag	$p = 0.183$	$p = 0.816$	$p = 0.185$	$p = 0.007$	$p = 0.150$	$p = 0.219$	$p = 0.171$	$p = 0.723$
White	$p = 0.255$	$p = 0.120$	$p = 0.774$	$p = 0.270$	$p = 0.962$	$p = 0.690$	$p = 0.036$	$p = 0.119$

* significant at 10%, ** significant at 5%, *** significant at 1%

Table 2. Inflation behavior (equation (6))

Dependent variable: π_t								
	Coefficient (*t*-statistic)							
	UK	CAN	NZL	SWE	CHI	POL	CZE	KOR
	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1996:Q1–2005:Q1	1994:Q4–2005:Q1	1994:Q1–2005:Q1	1990:Q1–2005:Q1
π_{t-1}	0.517***	0.276**	0.226**	0.370***	0.4171**	0.602***	0.528***	0.315***
	(4.967)	(2.626)	(2.016)	(3.288)	(2.725)	(8.259)	(4.128)	(3.661)
Δe_t	0.029**	0.291***	0.102***	0.098***	0.038	0.144***	0.049*	0.183***
	(1.817)	(5.928)	(4.163)	(3.741)	(1.613)	(4.426)	(1.969)	(8.481)
Y_t	0.225*	0.367**	0.424***	0.354**	0.426**	0.411**	0.420**	0.381**
	(2.562)	(2.312)	(3.434)	(2.266)	(2.666)	(2.286)	(2.634)	(2.483)
LM test								
1 lag	$p = 0.469$	$p = 0.139$	$p = 0.938$	$p = 0.182$	$p = 0.073$	$p = 1877$	$p = 0.417$	$p = 0.556$
2 lags	$p = 0.163$	$p = 0.143$	$p = 0.783$	$p = 0.390$	$p = 0.183$	$p = 0.132$	$p = 0.713$	$p = 0.649$
ARCH								
1 lag	$p = 0.451$	$p = 0.683$	$p = 0.037$	$p = 0.144$	$p = 0.254$	$p = 0.149$	$p = 0.657$	$p = 0.366$
White	$p = 0.464$	$p = 0.908$	$p = 0.001$	$p = 0.656$	$p = 0.487$	$p = 0.142$	$p = 0.973$	$p = 0.000$

* significant at 10%, ** significant at 5%, *** significant at 1%

Table 3. Exchange rate changes' behavior (equation (7))

Dependent variable: Δe_t								
	Coefficient (*t*-statistic)							
	UK	CAN	NZL	SWE	CHI	POL	CZE	KOR
	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1990:Q1–2005:Q1	1996:Q1–2005:Q1	1994:Q4–2005:Q1	1994:Q1–2005:Q1	1990:Q1–2005:Q1
Δe_{t-1}	0.169*	0.236*	0.402***	0.233*	0.286*	0.252	0.295**	0.272**
	(1.308)	(1.852)	(3.350)	(1.832)	(1.763)	(1.622)	(2.024)	(2.141)
LM test								
1 lag	$p = 0.129$	$p = 1$	$p = 0.791$	$p = 1$	$p = 0.545$	$p = 0.123$	$p = 1$	$p = 0.134$
2 lags	$p = 0.011$	$p = 0.144$	$p = 0.381$	$p = 0.109$	$p = 0.440$	$p = 0.273$	$p = 0.926$	$p = 0.194$
ARCH								
1 lag	$p = 0.839$	$p = 0.344$	$p = 0.093$	$p = 0.007$	$p = 0.204$	$p = 0.906$	$p = 0.791$	$p = 0.000$
White	$p = 0.380$	$p = 0.285$	$p = 0.094$	$p = 0.025$	$p = 0.437$	$p = 0.543$	$p = 0.649$	$p = 0.000$

* significant at 10%, ** significant at 5%, *** significant at 1%

Table 4. Optimal interest rate’s reaction function

Country/Time period	Control variable	G_t coefficients									g_t coefficients
UK											
$t=10$	$i_{10}=$	0.641471	Y_9	+	0.094759	π_9	+	0.000902	Δe_9		−0.819916
$t=1$	$i_1=$	0.641471	Y_0	+	0.124495	π_0	+	0.001291	Δe_0		−0.782816
CAN											
$t=10$	$i_{10}=$	6.407052	Y_9	+	0.575915	π_9	+	0.143332	Δe_9		−7.704448
$t=1$	$i_1=$	6.407052	Y_0	+	0.611910	π_0	+	0.161503	Δe_0		−7.371434
NZL											
$t=10$	$i_{10}=$	5.677081	Y_9	+	0.465871	π_9	+	0.084681	Δe_9		−6.772567
$t=1$	$i_1=$	5.677081	Y_0	+	0.483458	π_0	+	0.095159	Δe_0		−6.455116
SWE											
$t=10$	$i_{10}=$	0.208283	Y_9	+	0.059562	π_9	+	0.003704	Δe_9		−0.246583
$t=1$	$i_1=$	0.208283	Y_0	+	0.066665	π_0	+	0.004485	Δe_0		−0.218710
Average ($t=10$)		3.233472			0.299027			0.058155			–
Average ($t=1$)		3.233472			0.321632			0.065610			–
CHI											
$t=10$	$i_{10}=$	3.135002	Y_9	+	0.527595	π_9	+	0.013838	Δe_9		−3.937551
$t=1$	$i_1=$	3.135002	Y_0	+	0.600539	π_0	+	0.017477	Δe_0		−3.588953
POL											
$t=10$	$i_{10}=$	0.401215	Y_9	+	0.199842	π_9	+	0.012103	Δe_9		−0.480279
$t=1$	$i_1=$	0.401215	Y_0	+	0.266527	π_0	+	0.018403	Δe_0		−0.314516
CZE											
$t=10$	$i_{10}=$	3.712065	Y_9	+	0.908564	π_9	+	0.025066	Δe_9		−3.979941
$t=1$	$i_1=$	3.712065	Y_0	+	1.126445	π_0	+	0.035605	Δe_0		−4.629172
KOR											
$t=10$	$i_{10}=$	1.495730	Y_9	+	0.184139	π_9	+	0.029264	Δe_9		−1.893043
$t=1$	$i_1=$	1.495730	Y_0	+	0.199094	π_0	+	0.034180	Δe_0		−1.777083
Average ($t=10$)		2.186003			0.455035			0.020068			–
Average ($t=1$)		2.186003			0.548151			0.026416			–
F value ($t=10$)		0.34			0.53			1.21			–
F value ($t=1$)		0.34			0.82			1.01			–

Table 5. Deviations from the target of 2 percent annual growth for both GDP and inflation

	$\sum_{t=1}^{10}\left(\bar{Y}_t - Y_t^*\right)$	$\sum_{t=1}^{10}\left(\bar{\pi}_t - \pi_t^*\right)$
	$\mu_{1,t} = 1,\quad \mu_{2,t} = 1$	$\mu_{1,t} = 1,\quad \mu_{2,t} = 1$
UK	–0.096	0.100
CAN	–0.460	0.976
NZL	–0.554	0.998
SWE	–0.613	1.181
Average	–0.431	0.814
CHI	–1.348	1.690
POL	–2.168	1.735
CZE	–2.343	2.784
KOR	–0.687	1.250
Average	–1.637	1.865
F value	9.052	6.794

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