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# Reconsidering the natural rate hypothesis in a New Keynesian framework $\stackrel{\text{tr}}{\sim}$

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#### Abstract

This paper formulates a stylized New Keynesian model in which each individual firm can select the frequency of its price adjustments. The endogeneity of contract duration has a dramatic impact on the magnitude of the aggregate effects of steady-state inflation. With a plausible calibration of the magnitude of menu costs and other structural parameters, this model predicts a relationship between steady-state inflation and the frequency of price adjustment that is reasonably close to the empirical findings of cross-country studies. Furthermore, at moderate inflation rates, steady-state inflation generates relative price distortions that have a non-trivial impact on aggregate output, but this impact wanes and eventually disappears at much higher annual inflation rates because the frequency of price adjustment approaches that of the flexible-price economy. Published by Elsevier B.V.

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# 1. Introduction

Friedman (1968) noted that differing steady-state inflation rates will not keep output or employment permanently high or low relative to the natural-rate level that would prevail in the absence of nominal price stickiness in the relevant economies. Since then, the natural rate hypothesis had been widely accepted. But McCallum (2004) has remarked that the earlier consensus regarding the natural rate hypothesis has seemingly been implicitly overturned by the widespread adoption of the Calvo (1983) model of nominal price stickiness. For log-linearized New Keynesian Phillips curve implies that a positive inflation rate can attain a permanent positive output gap. A key mechanism behind this result is that the mean duration of fixing prices is exogenously determined in most New Keynesian models. Thus, one can easily guess that the absence of endogenous decisions on the timing or time duration of price changes might be responsible for the failure of the natural rate hypothesis in the New Keynesian model.

In this paper, we reconsider the natural rate hypothesis in the context of the recent New Keynesian models. In particular, we formulate a stylized New Keynesian model in which each individual firm can select the frequency of its price adjustments. In order to see this, we allow firms to choose a mean duration of their price changes. But firms are not allowed to choose the exact times of price changes, though price changes are assumed to be costly. In addition to homogenous menu cost, we analyze the case in which individual firms have different levels of menu cost.

The endogeneity of contract duration has a dramatic impact on the magnitude of the aggregate effects of steady-state inflation. First, we demonstrate that with moderate inflation rates, steady-state inflation generates relative price distortions that have a non-trivial impact on aggregate output, but this impact wanes and eventually disappears at much higher annual inflation rates because the frequency of price adjustment approaches that of the flexible-price economy. Second, it has been pointed out that the Calvo pricing model with exogenous contract structures may not perform reasonably in the steady-state analysis for economies with high inflation. For the model requires an upper bound of inflation rates in order to guarantee the internal consistency of the model, given an exogenous mean duration of contract. But allowing for endogenous mean duration of contract would enable one to perform steady-state analysis for economies with high inflation. Third, it is shown that as steady inflation rises, log-linearized Phillips curve gets steeper and thus becomes a vertical line. This is in contrast with the result of Ascari (2004) that the slope of the log-linearized Phillips curve falls with steady-state inflation in the Calvo model with exogenous contract duration.

In addition to the qualitative results discussed above, we use our model to ask if the Calvo model with endogenous contract structure can explain the observed relationship between the average inflation and the average frequency of price adjustment. For example, a cross-country evidence on the relationship between the average inflation and frequency of price changes, reported in Table 1, suggests that the mean duration of prices becomes shorter as average inflation rises, as noted in Golosov and Lucas (2007). We demonstrate that with a plausible calibration of the magnitude of menu costs and other structural parameters, our modelling framework's theoretic prediction on the relationship between average inflation and the frequency of price adjustment is consistent with the cross-country evidence in Table 1.

Economy	Sample period	Annual average CPI inflation (%)	Quarterly frequency of price changes (%) 26		
Euro Area	1995-2000	2			
United States	1998-2005	2	24		
United States	1988–1997	4	30		
Mexico	1995-1996	31	70		
Israel	1981–1982	75	80		
Israel 1978–1979		114	85		

Table 1							
International	comparison	of	price	adj	justment	free	uencies

Sources: Euro Area: Dhyne et al. (2005); United States: Nakamura and Steinsson (2006); Mexico: Gagnon (2006); Israel: Lach and Tsiddon (1992).

Our modelling framework is not new. The optimal duration of contracts has been extensively analyzed in many papers at micro and macro economics levels. In a broad sense, we follow the approach taken in Ball et al. (1988), Romer (1990), Ball and Mankiw (1994), and Ireland (1997). The difference from the previous works is that the optimal choice on the mean duration of contracts is analyzed in a completely non-linear structure with exact non-linear solutions.

The rest of the paper is organized as follows. Section 2 reviews the non-linear steadystate properties of a prototypical New Keynesian macro model. Section 3 presents an endogenous contract structure in which each firm chooses a mean-duration of its price contracts in order to maximize its expected discounted profit stream. Section 4 adds heterogenous menu-costs to the model. In Section 5, we briefly highlight implication of models with endogenous contract duration for log-linear dynamics. We conclude by summarizing possible directions of future research in Section 6.

#### 2. Exogenous contract structure

The New Keynesian model that we review in this section follows the exogenous contract structure of the prototypical Calvo model in which the average frequency of price changes is represented by an exogenous parameter. Furthermore, since we focus on the steady-state properties of the model, our analysis proceeds by directly considering the non-linear equations and does not require any log-linear approximations.

#### 2.1. Model specification

Each individual firm faces a downward-sloping demand curve. Given the downwardsloping demand curve, firms set their prices as monopolistic competitors. The consumption index denoted by  $C_t$  is assembled using a constant returns to scale technology of Dixit–Stiglitz aggregator form:

$$C_t = \left(\int_0^1 C_t(f)^{(\varepsilon-1)/\varepsilon} \,\mathrm{d}f\right)^{\varepsilon/(\varepsilon-1)}.$$

The Dixit-Stiglitz aggregator has a constant elasticity of substitution between different goods denoted by  $\varepsilon$ . The demand curve of each type of differentiated goods  $C_t(f)$  is

$$C_t(f) = \left(\frac{P_t(f)}{P_t}\right)^{-\varepsilon} C_t,$$

where the price level at period *t* is defined to be as

$$P_t = \left(\int_0^1 P_t(f)^{1-\varepsilon} \,\mathrm{d}f\right)^{1/(1-\varepsilon)}$$

We also assume that labor market is perfectly competitive and wages are fully flexible. The production function of an individual firm is linear in labor input

$$Y_t(f) = A_t L_t(f),$$

where  $A_t$  is the aggregate disturbance to labor productivity and  $L_t(f)$  is the amount of labor hired by firm f. As a result, the real marginal cost is identical across firms.

The preference at period 0 of the representative household is represented as follows:

$$\mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \left[ \frac{C_t^{1-\sigma} - 1}{1-\sigma} - \frac{L_t^{1+\chi}}{1+\chi} \right],$$

where  $\sigma$  is relative risk aversion,  $\chi$  is the inverse of labor supply elasticity and  $L_t$  is the amount of worked at period t. Furthermore, the complete contingent-claims market exist without any financial frictions. The inter-temporal marginal rate of substitution is therefore used as a stochastic discount factor for computing the expected present-value of future profit streams.

Given these demand and production structures, the Calvo model describes how firms set prices over time. During each period, only a fraction of all sellers,  $1 - \xi$ , can change prices during any period, with others holding their nominal prices fixed at their previous-period values. The probability of price change in a given time interval is constant and exogenously determined. The random duration of contract prices leads to an infinite-horizon maximization problem facing firm that set their prices:

$$\max_{P_t(f)} \mathbb{E}_t \sum_{k=0}^{\infty} (\xi\beta)^k (C_{t+k}/C_t)^{-\sigma} [(P_t(f)/P_{t+k})^{1-\varepsilon} C_{t+k} - MC_{t+k} (P_t(f)/P_{t+k})^{-\varepsilon} C_{t+k}].$$

The profit maximization with respect to prices then leads to the equality of the expected present-value of the current and future marginal revenues and the expected present-value of the current and future marginal costs. Table 2 summarizes equilibrium conditions of the model described above.

### 2.2. Real effects of steady-state inflation

Having described equilibrium conditions of the model with exogenous contract duration, we now present a full non-linear equilibrium relation between the steady-state inflation and output gap and then compare it with the corresponding relationship that is implied by the New Keynesian Phillips curve.

# Table 2 Equilibrium conditions of the model with exogenous contract duration

Price contract equation:  $E_{t} \sum_{k=0}^{\infty} \beta^{k} \xi^{k} \left(\frac{P_{t+k}}{P_{t}}\right)^{\epsilon} \left(\frac{P_{t}^{*}}{P_{t+k}} - \frac{\varepsilon}{\varepsilon - 1} MC_{t+k}\right) Y_{t+k}^{1-\sigma} = 0$ Real marginal cost:  $MC_{t} = C_{t}^{\sigma} L_{t}^{\chi}$ Aggregate production:  $C_{t} = Y_{t} = \frac{A_{t} L_{t}}{A_{t}}$ Aggregate price identity:  $1 = (1 - \xi) (\tilde{P}_{t}^{*})^{1-\varepsilon} + \xi \Pi_{t}^{\varepsilon - 1}$ Relative price distortion:

Relative price distortion:  $\Delta_t = (1 - \xi)(\tilde{P}_t^*)^{-\varepsilon} + \xi \Pi_t^{\varepsilon} \Delta_{t-1}$ 

Notation:  $\tilde{P}_t^*$ : relative price of contract price;  $MC_t$ : real marginal cost;  $P_t$ : aggregate price,  $Y_t$ : output.  $L_t$ : labor;  $\Delta_t$ : relative price distortion;  $C_t$ : consumption;  $\Pi_t$ : gross inflation;  $L_t(f)$ : labor of firms;  $\beta$ : discount factor;  $\varepsilon$ : demand elasticity;  $\chi$ : inverse of labor supply elasticity.

The set of equilibrium conditions summarized in Table 2 can be solved to show that steady-state output gap can be expressed in terms of steady-state inflation

$$x = -\frac{\chi}{\sigma + \chi} \log \Delta - \frac{1}{\sigma + \chi} \log \mu, \tag{1}$$

where the output gap, x, is the logarithmic deviation of output from its value in the steady state with zero inflation. Here, steady-state relative price distortion,  $\Delta$ , and average markup,  $\mu$ , are respectively determined by steady-state inflation

$$\Delta = \left(\frac{1-\xi}{1-\xi\Pi^{\varepsilon}}\right) \left(\frac{1-\xi}{1-\xi\Pi^{\varepsilon-1}}\right)^{-\varepsilon/(\varepsilon-1)},\tag{2}$$

$$\mu = \frac{\varepsilon}{\varepsilon - 1} \left( \frac{1 - \zeta \Pi^{\varepsilon - 1}}{1 - \zeta \Pi^{\varepsilon}} \right) \left( \frac{1 - \zeta \Pi^{\varepsilon - 1}}{1 - \zeta} \right)^{1/(\varepsilon - 1)},\tag{3}$$

where  $\Pi$  is the ratio of the current price level to the one-period lagged price level.

In the steady state with zero inflation, there is no relative price dispersion and all firms have the same markup  $\mu = \varepsilon/(\varepsilon - 1)$ . The aggregate average markup goes down slightly in a neighborhood of zero inflation and then rises with steady-state inflation. The relative price distortion is monotonically increasing in steady-state inflation. Eq. (1) thus implies that the output gap is negative in a steady-state with a sufficiently high positive inflation rate, though it is positive in a small neighborhood of zero inflation.

Having discussed the implication of non-linear equilibrium conditions for the steadystate relation between inflation and output gap, we turn to the discussion of the New Keynesian Phillips curve. Many studies have proceeded by considering a log-linear



Fig. 1. Output costs of steady-state inflation (relative to zero-inflation steady state). Note: this figure depicts the output cost of steady-state inflation in the exogenous contract duration model, where the inflation rate is expressed at annual rates in percentage points and the output cost is expressed as a percent deviation from the level of output in the zero-inflation steady state. The solid line corresponds to the exact non-linear solution of the model, while the dashed line shows the implications of the log-linearized New Keynesian Phillips curve.

approximation of the Calvo model around a steady state with a zero inflation rate, thereby obtaining the benchmark New Keynesian Phillips curve

$$\pi_t = \beta \mathsf{E}_t[\pi_{t+1}] + \kappa x_t,\tag{4}$$

where  $\pi_t$  is the one-period inflation rate (that is, the logarithmic change in the price index from the previous period), and  $x_t$  is the logarithmic deviation at period t of output from its value in the steady state with zero inflation. The slope of the NKPC is denoted by the composite parameter  $\kappa = (\sigma + \chi)(1 - \xi)(1 - \beta\xi)/\xi$ , involving the Calvo parameter  $\xi$  as well as the preference parameters  $\beta$ ,  $\sigma$ , and  $\chi$ .

As emphasized by McCallum (2004), the log-linearized NKPC fails to satisfy the natural rate hypothesis, because a non-zero constant rate of inflation is associated with a permanent deviation of real output from its natural rate:

$$x = \frac{(1-\beta)}{\kappa}\pi,\tag{5}$$

where  $\pi = \log \Pi$ . In particular, Eq. (5) implies that an increase in the rate of inflation leads to a permanent increase in the output gap. In this sense, local approximation yields a positive correlation between the steady-state inflation and the output gap. But we can demonstrate that an increase in the steady-state rate of inflation can decrease the steady-state level of output in the Calvo model.<sup>1</sup>

Fig. 1 compares a log-linear relation between inflation and output with its corresponding exact non-linear steady-state relation. Before proceeding further, it is noteworthy that each variable in all figures is expressed in terms of the logarithmic deviation of its steady state value in order to maintain the same unit for the log-linear approximation and the exact steady-state relation. The straight line corresponds to the linear relation summarized in

<sup>&</sup>lt;sup>1</sup>Ascari (2004), Casares (2004), Burnstein (2006), and Levin et al. (2006b) also emphasized that an increase in the steady-state rate of inflation can decrease the steady-state level of output in the Calvo model.

Eq. (5), while the dotted line represents its corresponding non-linear relation. Fig. 1 shows that an increase in steady-state inflation leads to an increased level of output so long as inflation remains within a neighborhood of zero inflation rate. This is true for both of the two cases. But in the case of exact non-linear solutions, the steady-state level of output reaches its maximum at a small positive inflation rate and then begin to decline as inflation rises. We can thus see that steady-state inflation raises output in a neighborhood of zero inflation rate. But this does not hold when inflation is sufficiently high. An important reason for this is that relative price distortion rises as steady-state inflation rises.

Fig. 2 depicts the effect of steady-state inflation on output, markup, relative price distortion, and labor. In this figure, we focus on exact non-linear steady-state equilibrium conditions, though each variable is expressed in terms of the logarithmic deviation of its steady state value. In the similar way as shown in Fig. 1, the steady state level of output remains below its level at the zero inflation rate when inflation is sufficiently high. Fig. 2 also shows that there is a range of inflation in which the steady state of output remains below its level at the zero inflation, while labor stays above its level at the zero inflation. The key mechanism behind this is that the steady-state level of relative price distortion rises with inflation, while relative price distortion is defined as the fraction of output that is



Fig. 2. Demand elasticity and the real effects of steady-state inflation. Note: this figure compares the real effects of steady-state inflation in the exogenous contract duration model using two alternative calibrations of the demand elasticity  $\varepsilon$ . In each panel, the specified variable is expressed in terms of the percent deviation from the zero-inflation steady state, and the inflation rate is expressed at an annual rate in percentage points. The solid line denotes the benchmark calibration of  $\varepsilon = 4.33$ , corresponding to a 30% markup in the zero-inflation steady state. The dashed line denotes the calibration of  $\varepsilon = 11$ , which implies a 10% markup in the zero-inflation steady state.

1350

foregone because of relative price dispersion.<sup>2</sup> As a result, steady-state levels of output and employment can move in the opposite direction as inflation rises.

Finally, it has been pointed out that the Calvo pricing model with exogenous contract structures may be of limited use in the steady-state analysis for economies with high inflation. As noted in the introduction, the reason for this is that the internal consistency of the model yields upper bounds of inflation rate. For example, notice that relative prices of lagged contract prices keep falling with a positive inflation rate, while the price level is an weighted average of infinite number of prices. Hence, the condition that an infinite number of different prices must be consistent with a positive relative price of contract price at a positive rate of inflation turns out to be binding under a certain range of inflation given fixed values of parameters. In particular, the definitions of the price level and relative price distortion lead to the following inequalities  $\zeta \Pi^{\varepsilon-1} < 1$  and  $\zeta \Pi^{\varepsilon} < 1$ , respectively.<sup>3</sup> The two equations thus act as constraints for steady-state inflation when  $\zeta$ ,  $\beta$ , and  $\varepsilon$  are exogenously determined. However, when  $\zeta$  is endogenously determined, they are not binding constraints even for high inflation.

#### 3. Endogenous contract structure with homogenous menu costs

Having described the real effects of steady-state inflation in the Calvo model with exogenous contract duration, we now turn to the Calvo model with endogenous contract duration. In doing so, we assume that firms choose the probability of their price changes in each period, following Romer (1990), Kiley (2000) and Devereux and Yetman (2002). The difference from theirs is that their optimization problems of choosing the arrival rate of price changes exploit quadratic loss functions of firms, while we do not rely on any approximation to the characterization of the optimization problem. We thus seek a full non-linear solution to the equilibrium average duration of fixing prices.

We now give a brief discussion of model specification and equilibrium concept employed in this section. First, we focus on deterministic steady states in which real quantities are constant over time. We do this because the primary aim of this paper is to analyze real effects of steady-state inflation. Hence, we assume that price changes incur fixed costs  $F_t = \omega Y$  in each period  $t = 0, 1, \dots, \infty$ . The physical costs of price adjustments are assumed to be identical across firms. Second, we restrict our analysis to a symmetric Nash equilibrium in which individual firms choose the same frequency of price adjustments. In order to state the symmetric Nash equilibrium more formally, suppose that a firm *j* is allowed to choose not only a new price but also an average frequency of its future price adjustments  $\xi_j$  by maximizing the discounted sum of profit streams, given that other firms choose  $\xi$ . The symmetric Nash equilibrium then requires the equality of  $\xi_j = \xi$  for all *j*. It is also important to note that the assumption of the deterministic steady-state leads firms to choose the same mean-duration of price contract when they are allowed to solve a new

<sup>&</sup>lt;sup>2</sup>See, for example, Goodfriend and King (1997), King and Wolman (1999), Woodford (2003) and Ascari (2004) for more detailed discussions on the relative price distortion in the recent optimizing sticky price models with staggered price-setting. Moreover, wage dispersion takes place in Erceg et al. (2000) because of a staggered wage-setting.

<sup>&</sup>lt;sup>3</sup>The inequalities of  $\xi\beta\Pi^{e} < 1$  and  $\xi\beta\Pi^{e-1} < 1$  result from the fact that the expected present-value of profits must not blow up in an equilibrium and the profit-maximization problem in the Calvo pricing model is an infinitehorizon maximization problem.

optimization problem in each period  $t = 0, 1, ..., \infty$ . However, this does not hold in a stochastic economy.<sup>4</sup>

In order to state the optimization problem of an individual firm formally, we let  $\tilde{P}_j^*$  denote the relative price of the profit maximizing price at period *t* for firms that choose  $\xi_j$  given  $\xi$  and  $\Psi_k(\tilde{P}_j^*/\Pi^k, \xi_j, \xi)$  be the present-value at period *t* of current and future profits for firms that re-optimize their prices at period t - k when they have chosen  $\tilde{P}_j^*$  and  $\xi_j$ . A recursive representation of  $\Psi_k(\tilde{P}_j^*/\Pi^k, \xi_j, \xi)$  is

$$\Psi_k(\xi_j,\xi) = \Phi(\tilde{P}_j^*/\Pi^k) - I_{\{k=0\}}\omega Y + \beta\{\xi_j \Psi_{k+1}(\xi_j,\xi) + (1-\xi_j)\Psi_0(\xi_j,\xi)\}$$
(6)

for  $k = 0, 1, ..., \infty$  and the indication function  $I_{\{k=0\}}$  satisfies  $I_{\{k=0\}} = 1$  if k = 0 and  $I_{\{k=0\}} = 0$  if  $k \neq 0$ . The one-period profit  $\Phi(\tilde{P}_i^*/\Pi^k)$  is given by

$$\Phi(\tilde{P}_j^*/\Pi^k) = [(\tilde{P}_j^*/\Pi^k)^{1-\varepsilon} - MC(\tilde{P}_j^*/\Pi^k)^{-\varepsilon}]Y.$$
(7)

It should be noted that firms choose not only mean contract period but also their contract prices. The relative price of nominal contract price is determined by the following first-order condition:

$$\tilde{P}_{j}^{*} = \frac{\varepsilon}{\varepsilon - 1} \frac{1 - \tilde{\zeta} \beta \Pi^{\varepsilon - 1}}{1 - \zeta \beta \Pi^{\varepsilon}} MC.$$
(8)

The contract price is a function of mean contract duration, inflation rate, and real marginal cost. Furthermore, in order to choose mean contract duration, individual firms that are allowed to change their prices maximize the following discounted sum of profits with respect to  $\xi_i$ :

$$\Psi_0 = \frac{1 - \xi_j \beta}{1 - \beta} \left[ \sum_{k=0}^{\infty} (\beta \xi_j)^k [(\tilde{P}_j^* / \Pi^k)^{1-\varepsilon} - MC(\tilde{P}_j^* / \Pi^k)^{-\varepsilon}] - \omega \right].$$
(9)

The symmetric Nash equilibrium then means that firm *j* chooses  $\tilde{P}_j^* = \tilde{P}^*$  and  $\xi_j = \xi$  for all *j* given that all other firms choose  $\tilde{P}^*$  and  $\xi$ .

Next, it would be worthwhile to describe how one can compute the aggregate real marginal cost. In order to do this, notice that the price level equation for the Calvo model implies that  $\tilde{P}^*$  should satisfy

$$\tilde{P}^* = \left(\frac{1 - \xi \Pi^{\varepsilon - 1}}{1 - \xi}\right)^{1/(1 - \varepsilon)}.$$
(10)

It also follows from the first-order condition of profit maximization that the aggregate real marginal cost is given by

$$MC = \left(\frac{\varepsilon - 1}{\varepsilon}\right) \frac{1 - \zeta \beta \Pi^{\varepsilon}}{1 - \zeta \beta \Pi^{\varepsilon - 1}} \tilde{P}^*.$$
(11)

<sup>&</sup>lt;sup>4</sup>In a stochastic economy, we can assume that firms maximize the unconditional expectation of the discounted sum of profit streams to choose an average frequency of price adjustments when their optimization problems need to be formulated without any approximation. In addition, if one uses a quadratic approximation to the profit function of individual firms together with linearized equilibrium conditions and stationary exogenous shocks, a time-invariant solution can be obtained without relying on the assumption of the once-and-for-all decision on the mean contract duration. In general, the optimization under a quadratic approximation to the profit function may not lead to the same solution that would have been obtained from the optimization without any approximation.



Fig. 3. Frequency of price adjustment in the endogenous contract duration model. Note: the dashed line denotes the relationship between steady-state inflation and the frequency of price adjustment in the endogenous contract duration model, where inflation is expressed at an annual rate in percentage points, and the adjustment frequency indicates the percentage of firms that modify their prices in a given quarter. Each symbol denotes the empirical frequency of price adjustment for the specified economy and sample period.

As a result, we can express the equilibrium average frequency of price adjustment as a function of steady-state inflation.<sup>5</sup>

Fig. 3 demonstrates the relationship between steady-state inflation and equilibrium probability of price adjustment. The vertical axes represent the fraction of prices changed in each quarter. The horizontal axes denote the annual inflation rate. Fig. 3 indicates that higher steady-state inflation raises the average frequency of price changes. We also plot several international observations on the relationship between the inflation and frequency of price adjustments, which are summarized in Table 1.

The data reported in Table 1 are comparable to those used in Golosov and Lucas (2007) except that we include Nakamura and Steinsson (2006) for the Unites States. In particular, Nakamura and Steinsson (2006) obtain much lower adjustment frequencies than the earlier studies of Bils and Klenow (2004) and Klenow and Kryvtsov (2005) because of their different treatment about temporary sales, which are particularly important for some US retail sectors. Golosov and Lucas demonstrated that menu-costs models can replicate the cross-country observations on the relationship between inflation and frequency of price changes.

Fig. 3 shows that the model analyzed in this paper predicts a relationship between steady-state inflation and the frequency of price adjustment that is consistent with the cross-country data in Table 1. The endogenous duration model successfully replicates the findings of Nakamura–Steinsson regarding the lower frequency of price adjustment that was associated with the decline in US consumer inflation over their two sub-samples.

<sup>&</sup>lt;sup>5</sup>It should be admitted that we do not provide a rigorous discussion on the possibility of multiple equilibria. In relation to this, the real marginal cost equation specified above is derived under the assumption that there are no endogenous fluctuations of real output. Given this assumption, our solution procedure finds a value of  $\xi$  satisfying  $\xi = \arg \max_{\xi_i} \Psi_0(\tilde{P}_i^*, \xi_i, \xi)$ .



Fig. 4. Comparing the real effects of steady-state inflation under endogenous vs. exogenous contract duration. Note: this figure depicts the real effects of steady-state inflation in the endogenous contract duration (solid line) compared with those implied by the exogenous contract duration model (dashed line). In each panel, the specified variable is expressed as a percent deviation from the zero-inflation steady state, and the inflation rate is expressed at an annual rate in percentage points.

Besides, as noted in the introduction, at moderate inflation rates, steady-state inflation generates relative price distortions that have a non-trivial impact on aggregate output, but this impact wanes and eventually disappears at much higher annual inflation rates because the frequency of price adjustment approaches that of the flexible-price economy.<sup>6</sup>

Fig. 4 plots effects of steady-state inflation on output, markup, relative price distortion and labor in models with endogenous and exogenous contract duration for a range of low and mild inflation. The straight line corresponds to endogenous contract duration, while the dotted line represents exogenous contract duration. As shown in Fig. 4, the presence of endogenous contract structure reduces the magnitude of the effect on output, markup, and relative price distortion of steady-state inflation. Even with the introduction of endogenous contract structure, we can still find a small range of inflation around zero inflation in which there exists a positive relationship between inflation and output. Fig. 5 plots output,

<sup>&</sup>lt;sup>6</sup>We use the parameter values of Dotsey et al. (1999) as a benchmark calibration. For example, we set  $\beta = 0.984$ , which implies a real return of 6.5% annually. We also set  $\varepsilon = 4.33$  so that the markup in the steady-state with zero inflation is 1.3. The size of menu cost is set to be 2.9% of labor input. Since we assume that production function is linear in labor, it means that menu cost is 2.9% of real output. In addition, Levy et al. (1999) and Zbaracki et al. (2004) provide empirical works on costs of price adjustment.



Fig. 5. The emergence of the natural rate hypothesis in the endogenous contract duration model. Note: this figure depicts the real effects of steady state inflation in the endogenous contract duration model. Each real variable is expressed as a percent deviation from the zero-inflation steady state, while the inflation rate is expressed at an annual rate in percentage points.

markup, relative price distortion and labor for an extended range of inflation rate. Fig. 5 indicates that markup and relative price distortion return to their values at zero inflation as inflation becomes very high.

The implications of endogenous contract duration for the real effect of steady-state inflation can be summarized as follows. First, the output effect of inflation becomes dramatically small for high rates of inflation, relative to models with exogenous contract duration. Second, there is a threshold value of the steady-state inflation rate that determines whether or not the steady state inflation has influence on output. Moreover, as shown in Fig. 5, inflation raises output under a range of high positive rates of inflation. In this region, markup and relative price distortion decline. Third, steady state inflation can reduce output for a range of low inflation rates even in models with endogenous contract duration.

It also should be mentioned that output in the steady state with zero inflation can differ from its level at the inflation rate that makes the natural rate hypothesis hold. The difference arises because of menu cost. Specifically, the output level with zero inflation is smaller than that of the steady state with an inflation rate that makes the natural rate hypothesis hold, if all firms fix their prices permanently in the steady state with zero inflation. In order to see this, notice that the first-order condition for labor supply at a deterministic steady state can be written as  $Y = (MC/(\Delta^{\chi}(1-s_F)^{\sigma}))^{1/(\sigma+\chi)}$ , where  $s_F$  is the share of the aggregate menu cost in real output. Thus, the output level at the steady state in



Fig. 6. The frequency of price adjustment under alternative calibrations. Note: this figure shows how the calibration of key parameters influences the relationship between steady-state inflation and the frequency of price adjustment in the endogenous contract duration model, where inflation is expressed at an annual rate in percentage points and the adjustment frequency indicates the percentage of firms that modify their prices in a given quarter. The left panel compares the benchmark calibration of the menu cost parameter ( $\omega = 2.9\%$ ) with two alternative values ( $\omega = 0.6\%$  and 5%). The right panel compares the benchmark calibration of the demand elasticity ( $\varepsilon = 4.33$ ) with two alternative values ( $\varepsilon = 3$  and 11).

which all firms choose a flexible-price strategy is higher than that of the steady state in which all firms fix their prices permanently. Another consequence of the presence of menu cost is that output increases are not necessarily associated with consumption increases, as can be seen in Fig. 5.

Fig. 6 depicts how the average frequency of price adjustment is affected by parameter values. First, the average frequency of price adjustment declines as the magnitude of menu costs decreases. Second, the average frequency of price adjustment declines as the elasticity of demand rises. For a higher elasticity of demand raises competition in goods market, thereby leading to more frequent price changes given other parameter values.

# 4. Endogenous contract structure with heterogenous menu costs

Having discussed the endogenous contract structure with homogenous menu-costs, the analysis of this section moves onto the case in which individual firms have different levels of menu-cost.

### 4.1. Conceptual issues

In this section, we briefly discuss issues associated with the specification of heterogenous menu-costs. Recent menu-costs models take into account some heterogenous aspects of

individual firms for several different reasons. First, Danziger (1999) and Gertler and Leahy (2005) use the independence of idiosyncratic productivity shocks to make price adjustments staggered, while they are random walks so that the variances of relative prices grow linearly over time. Golosov and Lucas (2007) also show that it is important to include idiosyncratic shocks in menu-cost models, in order to match the empirical evidence that a significant fraction of firms make price adjustment under low inflation. What these papers have in common regarding the specification of menu-costs is that menu costs are identical across individual firms. It thus means that the presence of idiosyncratic shocks plays an important role in generating staggered price-setting of firms over time.

Second, Dotsey et al. (1999) allow for random shocks to fixed costs of price adjustments. Thus, the staggered price-setting behavior of firms in their model depends on random shocks to fixed costs of price adjustment, rather than idiosyncratic productivity shocks. The presence of random shocks to menu-costs, however, means that the size of menu-costs may not be a characteristic of each individual firm. In relation to this, we assume that each individual firm can have a different level of menu-costs, which can be viewed as a characteristic of an individual firm.

A set of recent papers have combined time-dependent pricing models with statedependent pricing models. Ireland (1997) and Devereux and Siu (2005) include fixed price-adjustment costs into optimizing sticky price models with the Taylor-type staggered price-setting, though their specifications of menu costs are not the same. For example, Devereux and Siu posit that fixed costs of price adjustment are stochastic and firms do not observe realized costs of price adjustment when they set their prices, whereas Ireland assumes that individual firms have an identical level of price adjustment cost. In this paper, however, we do not allow the possibility that firms can choose the timing of a price change depending on the realization of states.

Instead, we permit firms to choose the arrival rates of their price changes. In relation to this, one may point out that modelling an endogenous choice on the exact time duration of contracts would be more realistic. But we simply restrict our analysis to the Calvo pricing structure, which has been widely used in recent New Keynesian macro models. Another reason why we maintain such a time-dependent structure is associated with a set of recent empirical works on the cause of price stickiness. More explicitly, a set of recent empirical works rely on the interview method as a way of finding out about the cause of price rigidity, following Blinder et al. (1998). In order to apply the interview method, he explained selected theories of sticky prices to managers in face-to-face interviews and assumed that they would recognize the line of reasoning when it came close to their way of thinking. A candidate theory of sticky prices included in the interviews is explicit and *implicit* contracts. For example, firms have contractual arrangements with their customers, in which they guarantee to offer the product at a specific price. An explanation why firms might engage in such agreements is that they want to build up long-run customer relationships. This should discourage customers from shopping elsewhere, stabilizing the firms' future sales. Customers are attracted by a constant price because it helps to minimize transaction costs (e.g. shopping time). Thus, customers focus on the long-run average price rather than on the spot price. In relation to contract theory, Kwapil et al. (2005) report that explicit contracts are indeed widely used by Austrian firms.

Furthermore, there is a trade-off between the imposition of restrictions on the optimal choice problem and the computational complexity. The most completely unrestricted optimization problem is to let each firm choose a different frequency of price changes

depending on the magnitude of its menu-cost. But such a completely unrestricted optimization problem raises computational complexity, though it is preferable. In order to yield a tractable approach, we consider only the simplest case in which only two pricing mechanisms are available for firms. More explicitly, one is the prototypical Calvo pricing mechanism with an optimized probability of price changes and the other is a Calvo contract with indexation.

# 4.2. Model specification

Firms are divided into two groups; one is firms with non-zero menu-cost and the other is firms with zero menu-cost. In order to formalize the analysis, we assume that a fraction of firms,  $(1 - \lambda)$ , should pay a fixed cost  $F_t = \omega Y$  whenever they change prices, while the other fraction of firms,  $\lambda$ , do not pay any physical cost. Moreover, we still restrict our analysis to a symmetric Nash equilibrium in which individual firms with non-zero menu cost choose the same frequency of price adjustment.

As shown in Table 3, the optimization problem of firms with non-zero menu cost is basically identical to the one we have described in the previous section. Moreover, since we seek a symmetric Nash equilibrium, firms with non-zero menu cost choose the same price and mean contract duration when they are allowed to do so. In addition, firms with zero menu cost always choose a flexible price contract and thus their markups are constant over time.

Table 3 Equilibrium conditions of the model with heterogeneous menu costs

Price contract equation for multi-period contract:  

$$E_t \sum_{k=0}^{\infty} \beta^k \xi^k \left( \frac{P_{t+k}}{P_t} \right)^{\varepsilon} \left( \frac{P_{st}^*}{P_{t+k}} - \frac{\varepsilon}{\varepsilon - 1} M C_{t+k} \right) Y_{t+k}^{1-\sigma} = 0$$

~1\_0

Real marginal cost:  $MC_t = C_t^{\sigma} L_t^{\chi}$ 

Aggregate production:

$$C_t = Y_t = \frac{A_t L_t}{\Delta_t}$$

Aggregate price identity:

$$1 = \lambda (P_{ft})^{1-\varepsilon} + (1-\lambda)P_{st}^{\prime}$$

$$\tilde{P}_{st}^{1-\varepsilon} = (1-\xi)(\tilde{P}_{st}^*)^{1-\varepsilon} + \xi \Pi_t^{\varepsilon-1} \tilde{P}_{st-1}^{1-\varepsilon}$$

Relative price distortion:

$$\Delta_t = \lambda (P_{ft})^{-\varepsilon} + (1 - \lambda) \Delta_{st}$$

$$\Delta_{st} = (1 - \xi)(\tilde{P}_{st}^*)^{-\varepsilon} + \xi \Pi_t^{\varepsilon} \Delta_{st-1}$$

Notation:  $\tilde{P}_{st}^*$ : relative price of multi-period contract price;  $\tilde{P}_{ft}^*$ : relative price of one-period contract price;  $MC_t$ : real marginal cost;  $P_t$ : aggregate price,  $Y_t$ : output.  $L_t$ : labor;  $\Delta_t$ : relative price distortion;  $C_t$ : consumption;  $\Pi_t$ : gross inflation;  $L_t(f)$ : labor of firms;  $\beta$ : discount factor;  $\varepsilon$ : demand elasticity;  $\chi$ : inverse of labor supply elasticity.

Table 3 also shows that in the presence of firms with zero menu cost, price level and relative price distortion become more complicated than those of the model with homogenous menu cost. Furthermore, the aggregate real marginal cost is affected by the magnitude of  $\lambda$ . Because of this, the pricing behavior of flexible-price firms affects that of firms with non-zero positive menu cost. In order to see this, notice that we can combine the first-order condition of prices with the definition equation of  $\tilde{P}_s$  to yield

$$\tilde{P}_{s} = \frac{\varepsilon}{\varepsilon - 1} MC \left( \frac{1 - \zeta \Pi^{\varepsilon - 1}}{1 - \zeta} \right)^{-1/(1 - \varepsilon)} \left( \frac{1 - \zeta \beta \Pi^{\varepsilon - 1}}{1 - \beta \zeta \Pi^{\varepsilon}} \right).$$
(12)

In addition, the relative price of flexible-price firms can be written as  $\tilde{P}_f^* = (\varepsilon/(\varepsilon - 1))MC$ . Substituting these two equations into the definition of the price level specified in Table 3 and then rearranging the resulting equation, we can express the real marginal cost in terms of steady-state inflation:

$$MC = \left(\frac{\varepsilon - 1}{\varepsilon}\right) (\lambda + (1 - \lambda)Z)^{1/(\varepsilon - 1)},$$
(13)

where Z is defined as

$$Z = \left(\frac{1-\xi}{1-\xi\Pi^{\varepsilon-1}}\right) \left(\frac{1-\xi\beta\Pi^{\varepsilon-1}}{1-\xi\beta\Pi^{\varepsilon}}\right)^{1-\varepsilon}.$$
(14)

Having shown that the aggregate real marginal cost is affected by the size of  $\lambda$  and each firm takes into account its changes when they set contract price and duration, we can see that the pricing behavior of firms with non-zero menu cost is affected by that of firms with zero menu cost.



Fig. 7. Heterogenous menu costs and the frequency of price adjustment. Note: this figure shows how the presence of flexible-price firms (that is, firms with zero menu costs) influences the relationship between steady-state inflation and the frequency of price adjustment for firms with positive menu costs. Inflation is expressed at an annual rate in percentage points, while the adjustment frequency indicates the percentage of firms with positive menu costs that modify their prices in a given quarter. The solid line corresponds to the case in which no firms have zero menu costs ( $\lambda = 0$ ), while the dashed line represents the case in which 95% of firms have zero menu costs ( $\lambda = 0.95$ ).



Fig. 8. Slope of the New Keynesian Phillips curve under endogenous vs. exogenous contract duration. Note: this figure compares the influence of steady-state inflation on the slope of the log-linearized Phillips curve in the model with endogenous contract duration (solid line) and in the model with exogenous contract duration (dashed line), where inflation is expressed at an annual rate in percentage points. In the exogenous contract duration model, the pricing decisions of individual firms are only well-defined for values of steady-state inflation below the threshold denoted by the starred vertical line.

# 4.3. Results

As shown in Figs. 7 and 8, a change in the fraction of firms with zero menu cost seems to have insignificant impacts on the pricing behavior of firms with a non-zero constant menu cost, though a rise in the fraction of firms with zero menu cost leads to more frequent price changes of firms with non-zero constant menu cost.<sup>7</sup> As noted earlier, the key mechanism behind this is that the fraction of firms with zero menu cost affects the aggregate variables including the aggregate real marginal cost and hence influences the pricing behavior of firms that have non-zero constant menu cost. But this does not have significant impacts.

# 5. Implications for log-linear dynamics

In this section, we briefly discuss implications of our analysis for the first-order dynamics of the aggregate inflation. In so doing, we begin with the discussions on the role of indexation in the specification of the Phillips curve equation. We do this for the following reason. The steady-state analysis employed in the previous sections can be applied to both indexed sticky-price and flexible-price contracts, if prices are fully indexed. But if we move onto stochastic economies, the difference between indexed and flexible-price contracts becomes more apparent. Besides, since trend inflation has significant effects on the loglinear dynamics, it would be interesting to see the effect of allowing for endogenous contract duration on the log-linear dynamics.

#### 5.1. Exogenous contract duration

The Calvo model assumes that only a fraction of all sellers can make price adjustments during any period, with others holding their nominal prices fixed at their previous-period

<sup>&</sup>lt;sup>7</sup>The calibration of parameters used for Figs. 7 and 8 proceeds in the following way. The share of menu cost in output for firms with non-zero constant menu-cost is set to be  $\omega = 0.029$ . In addition,  $\varepsilon = 4.33$  and  $\beta = 0.984$ . Moreover, we assume a logarithmic utility function for consumption and a quadratic function for labor.

values. In the Calvo model, log-linearizing the optimization conditions of sellers around the steady state with zero inflation rate leads to the prototypical New Keynesian Phillips curve equation:

$$\pi_t = \beta \mathcal{E}_t[\pi_{t+1}] + \kappa x_t. \tag{15}$$

As noted earlier, the Phillips curve equation then implies that it is possible to maintain a constant non-zero value of the output gap permanently by setting  $\pi_t = \pi$  from period t onward. The natural rate hypothesis thus fails in the prototypical New Keynesian Phillips curve equation.

Meanwhile, indexation plays an important role in recovering the natural rate hypothesis in the New Keynesian Phillips curve. For example, suppose that firms in the Calvo model index their prices to steady-state inflation in the period when they are not allowed to re-optimize their prices. The introduction of such a simple indexation replaces the prototypical New Keynesian Phillips curve with the following equation:

$$\pi_t - \pi = \beta(E_t[\pi_{t+1}] - \pi) + \kappa x_t.$$
(16)

The Phillips curve equation (16) then implies that setting  $\pi_t = \pi$  from period t onward no longer results in a non-zero steady-state value of the output gap. The New Keynesian Phillips curve equation (16) thus satisfies Friedman's weaker version of the natural rate hypothesis.

Furthermore, suppose that firms index their prices to the expected inflation conditional on their lagged information set instead of using steady state inflation. Specifically, the full indexation to expected inflation leads to the following Phillips curve equation:

$$\pi_t = \mathcal{E}_{t-1}[\pi_t] + \kappa x_t. \tag{17}$$

The key difference between Eqs. (16) and (17) is whether steady-state inflation or expected inflation is used for indexing prices. The resulting difference in terms of their implications for the effectiveness of monetary policy is remarkable. For the use of expected inflation for indexing prices in the Calvo pricing model yields a variant of the Lucas's aggregate supply curve. A policy implication of Eq. (17) is that monetary policy affects real output, to the extent which it generates unexpected changes in inflation. In other words, only unexpected changes in the monetary policy that generate unexpected changes in the current inflation rate can influence the real output. It is thus evident that a variant of the Lucas's curve (17) satisfies the natural rate hypothesis.

Firms can use lagged inflation to update their prices:

$$\pi_t - \delta \pi_{t-1} = \beta(\mathbf{E}_t[\pi_{t+1}] - \delta \pi_t) + \kappa x_t, \tag{18}$$

where  $\delta$  measures of the degree of indexation. For example, the full indexation corresponds to  $\delta = 1$ , while an incomplete indexation satisfies  $0 < \delta < 1$ . In particular, a permanent shift in the steady state inflation does not have any permanent effect on output gap in the long-run in the case of full indexation to lagged inflation, which has been used in many New Keynesian macro models in order to increase inflation persistence.<sup>8</sup>

<sup>&</sup>lt;sup>8</sup>The recent dynamic indexation includes not only a full indexation to lagged inflation as is done in Woodford (2003), Christiano et al. (2005), and Levin et al. (2006a) but also the optimal indexation of Calvo et al. (2003). In addition, Bakhshi et al. (2004) analyze the Phillips curve that is derived from a state dependent pricing model. Moreover, see Cogely and Sbordone (2005) for empirical work on the relationship between trend inflation and Phillips curve. Ascari and Ropele (2005) also discuss the relationship between trend inflation and optimal policy.

In summary, it has been shown that indexation is an important mechanism to make the natural rate hypothesis hold in the New Keynesian Phillips curve. But the difficulty associated with indexation is that while indexation requires all firms to change prices in each period, many microeconomic empirical studies indicate that many individual firms tend to fix their prices for more than one quarter.

#### 5.2. Endogenous contract duration

Having discussed implications of indexed contracts, we now discuss consequences of flexible-price contracts with endogenous contract duration on the slope of Phillips curve. In order to do so, we follow the approach of Ascari (2004) that log-linearize equilibrium conditions around steady states with non-zero inflation rate in order to analyze the effect of trend inflation on the NK Phillips curve. Specifically, we have the following Phillips curve equation:

$$\pi_t = \beta \mathcal{E}_t[\pi_{t+1}] + \lambda_{mc}(\Pi)\hat{m}c_t + \lambda_u(\Pi)u_t, \tag{19}$$

where  $u_t$  is an endogenous disturbance term that depends on current and future inflation and output and  $\lambda_{mc}$  and  $\lambda_u$  are defined as

$$\lambda_{mc}(\Pi) = \frac{(1 - \xi(\Pi)\Pi^{\varepsilon - 1})(1 - \beta\xi(\Pi)\Pi^{\varepsilon})}{\xi(\Pi)\Pi^{\varepsilon - 1}}, \quad \lambda_u(\Pi) = \beta(1 - \Pi)(1 - \xi(\Pi)\Pi^{\varepsilon - 1}).$$
(20)

Before proceeding further, we can see that the coefficient of the real marginal cost is subject to similar constraints for inflation described in Section 3. The sufficient condition is  $\xi \Pi^{\varepsilon} < 1$  when inflation is positive. When inflation is high, this constraint can be binding in the case of exogenous contract duration. For example, when we set  $\xi = 0.75$  and  $\varepsilon = 4.33$ , the constraint implies that the annual steady-state inflation rate should be less than 30%. The upper bound also becomes 19.65% with  $\varepsilon = 6$  and  $\xi = 0.75$  and 10.98% with  $\varepsilon = 6$  and  $\xi = 0.85$ .

As shown in Fig. 8, the effect of trend inflation on the slope of the Phillips curve in the model with endogenous contract duration is dramatically different from that of the model with exogenous contract duration. In order to see this, notice that the size of  $\lambda_{mc}(\Pi)$  declines as inflation rises in the case of exogenous contract duration. This result is in line with Ascari (2004). In addition, the slope of the Phillips curve depends on assumed values of  $\xi$  in the case of exogenous contract duration. Specifically, a rise in the mean duration of contract decreases the slope of the Phillips curve.

In contrast,  $\lambda_{mc}(\Pi)$  rises with the aggregate inflation in the case of endogenous contract duration. The slope of the Phillips curve therefore rises as trend inflation rises. Furthermore, the size of the slope parameter becomes large as inflation approaches the threshold value in which the natural rate hypothesis holds.

# 6. Directions for future research

We have demonstrated that a modelling framework with endogenous selection on the mean duration of contract leads the natural rate hypothesis to hold when steady state inflation is high, while it fails with exogenous contract structure. Besides, allowing for heterogenous menu costs results in a shorter average mean duration of contract through interactions of firms it generates.

We have assumed that a fraction of firms change their prices at the steady state with zero inflation. We do this by restricting the set of the average frequency of price changes that individual firms can choose. The first issue would be therefore to find an endogenous mechanism that makes a significant fraction of firms change prices at the steady state with zero inflation. In particular, the presence of firm-specific shocks to productivity and demand can have a fraction of firms change prices at the steady state with zero inflation. It would be thus interesting to analyze the effect of idiosyncratic productivity and demand shocks on the aggregate frequency of price changes.

Furthermore, our analysis has proceeded with non-stochastic cases, in order to focus on economic environments directly relevant for the natural rate hypothesis, though it can be extended to stochastic economies. In particular, we can analyze the effect of the aggregate volatility on the average frequency of price changes as well as its associated implication for monetary policy. For example, a local quadratic approximation to the profits of individual firms together with log-linear approximation to equilibrium conditions can be used to show that firms may prefer more frequent price changes as inflation variability rises. In doing so, the systematic part of monetary policy may play an important role in the determination of how quickly firms adjust the average time duration of price changes in stochastic economies. It means that changes in monetary policy regime may have significant impacts on the average frequency of price adjustment, which is absent in the Calvo model with exogenous contract duration.

It also should be mentioned that our modelling framework can be easily incorporated into recent empirical DSGE models such as Smets and Wouters (2003), Christiano et al. (2005), and Levin et al. (2006a). These models include Calvo-type pricing structure, while the mean duration of prices and timing of price changes in their models are exogenously determined. In relation to this, an advantage of the modelling strategy adopted in this paper is to make analytically tractable solutions of dynamic equilibrium models with complicated decision problems on pricing mechanism, thereby improving the flexibility of model specification.<sup>9</sup> Although the modelling framework leads to a tractable non-linear solution of the model, we can also use log-linear approximation around a steady state with low inflation in order to analyze effects of exogenous shocks as well as policy changes. It then facilitates the estimation of the model analyzed in this paper.

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<sup>&</sup>lt;sup>9</sup>We have combined elements of time-dependent and state-dependent pricing models to allow firms to change their pricing mechanisms occasionally, taking into account fixed costs of price adjustments. Thus, our modelling framework builds on the works of Ball et al. (1988), Ball and Mankiw (1994), Ireland (1997), Willis (2002), and Devereux and Siu (2005). In addition, examples of state-dependent pricing models include Seshinski and Weiss (1977), Caplin and Spulber (1987), Caplin and Leahy (1991), Caballero and Engel (1991) and Dotsey and King (2005) etc.

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