

# Incomplete Price Adjustment and Inflation Persistence

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## Abstract

This paper proposes a sticky inflation model in which inflation persistence is endogenously generated from the optimizing behavior of forward-looking firms. Although firms change prices periodically, their ability to fully adjust them in response to changes in economic conditions is assumed to be constrained due to the presence of managerial and customer costs of price adjustment. In essence, the model assumes that price stickiness arises from both the frequency and size of price adjustments. We estimate the model using Bayesian techniques. Our findings strongly support both sources of price stickiness in the U.S. data. The model performs well in matching microeconomic evidence on price setting, particularly regarding the size and frequency of price changes. The paper also shows how incomplete price adjustments in a staggered price contracts model limit the contribution of expectations to inflation dynamics: it generates the delayed response of inflation to demand and monetary shocks, and the observed “reverse dynamic” correlation between inflation and economic activity.

Keywords: Inflation Persistence, Phillips Curve, Sticky Prices, Convex Costs, Incomplete Price Adjustment, Infrequent Price Adjustment.

JEL Classification: E31

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# 1 Introduction

The standard New Keynesian Phillips curve (NKPC) based on the optimizing behavior of price setters in the presence of nominal rigidities is mostly built on the models of staggered contracts of John B. Taylor (1979, 1980) and Guillermo Calvo (1983), as well as the quadratic adjustment cost model of Julio Rotemberg (1982). This framework is broadly used in the analysis of monetary policy. Price rigidity works as the main transmission mechanism through which monetary policy impacts the economy.

Although the NKPC has some theoretical appeal, there is growing concern on its empirical shortcomings regarding the ability to match some stylized facts on inflation dynamics and the effects of monetary policy. In particular, the standard NKPC models have been criticized due to the failure to generate inflation persistence.<sup>1</sup> Accordingly, although the price level responds sluggishly to shocks, the inflation rate does not. In addition, these models do not yield the result that monetary policy shocks cause a delayed and gradual effect on inflation. Fuhrer and Moore (1995) and Nelson (1998), among others, suggest that in order for a model to fully explain the time series properties of aggregate inflation and output, it requires that not only the price level but also the inflation rate be sticky.

In response to those critiques, this paper proposes a microfounded sticky inflation model that is able to endogenously generate inflation persistence as a result of the optimizing behavior of forward-looking firms. In addition, the model implies that monetary policy shocks first impact economic activity, and subsequently inflation but with a long delay, reflecting inflation inertia. The model is also able to capture the observed joint dynamic correlation between inflation and output gap.

We consider that firms face two sources of price rigidities that are related to both the inability to change prices frequently and the cost of sizable adjustments. Calvo (1983)'s staggered price setting has been the most frequently used framework in the literature to derive the NKPC, with a fraction of firms completely adjusting their prices to the optimal level at discrete time intervals. Another popular framework is Rotemberg (1982) in which firms set prices to minimize deviations from the optimal price subject to quadratic frictions of price adjustment. While both the Calvo pricing and the quadratic cost of price adjustment are designed to model sticky prices, the former is related to the frequency of price changes while the latter is associated with the size of price changes. In addition, these models have different implication for the frequency of price changes: while Calvo's model implies staggered price setting, Rotemberg's model yields continuously price adjustment.

Costs of price adjustment might arise from managerial costs (information gathering and decision making) and customer costs (negotiation, communication, 'fear of upsetting customer's, etc.). For example, Mark J. Zbaracki, and Mark Ritson, Daniel Levy, Shantanu Dutta, and Mark Bergen (2004), using data from a large U.S. industrial manufacturer, document evidence that those costs of price adjustment are sizable and convex. In contrast to the implication of the Rotemberg pricing, the company that faces convex costs of price adjustment does not change prices continuously but annually because "it is not the culture" in that industry. The culture instead implies that prices are fixed by implicit

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<sup>1</sup>See, for example, Jeffrey C. Fuhrer and George Moore 1995, Edward Nelson 1998, Bennett T. McCallum 1999, Jordi Gali and Mark Gertler 1999, Gregory N. Mankiw 2002, Karl Walsh 2003, Argia Sbordone 2007, Jeremy Rudd and Karl Whelan 2005, 2006, 2007, Ignazio Angeloni, Luc Aucremanne, Michael Ehrmann, Jordi Gali, Andrew Levin, and Frank Smets 2006, among several others.

contracts for several periods. This is also found in a survey of around 11,000 firms in the Euro area by Fabiani et al. (2005), in which implicit and explicit contracts theories were ranked, respectively, first and second among the explanations for price stickiness.

The proposed model combines staggered price setting and quadratic costs of price adjustment in a unified framework. Firms face two decision problems: when to change prices - associated with the Calvo pricing; and how much to change prices - related to quadratic costs of price adjustment. Firms face quadratic adjustment costs only when they decide to change prices, which rather than fixed, are proportional to the magnitude of the change. The solution of the model implies that, first, prices are not continuously adjusted and, second, firms that are able to change prices do not fully adjust them due to the presence of convex adjustment costs. Inflation persistence is endogenously generated as consequence of this incomplete and infrequent price adjustment.

Several authors have proposed alternative price settings that can account for some of the empirical facts on inflation and output. The most popular ones are extensions of Calvo's staggered prices or contracts based on sticky information or backward indexation rules. These models assume that a fraction of the firms could set their prices optimally each period while the rest adjusts prices according to past aggregate inflation (hybrid NKPC models) or adjusts prices based on outdated information (sticky information models). Although these models are able to generate inflation persistence, either they also imply that prices adjust continuously<sup>2</sup>and/or that a fraction of the firms is backward-looking (see, e.g., Christiano, Eichenbaum, Evans 2005, and Smets and Wouters 2003, 2007). The empirical implication that prices change frequently in these models contradicts widespread micro-data studies. A recent extensive literature on microdata shows pervasive evidence of infrequent price adjustments. The finding across countries and different data sources is that firms keep prices unchanged for several months.<sup>3</sup>

Our sticky inflation model implies that current inflation is related to inflation expectations, lagged inflation, and real marginal cost or output gap. In contrast to the Calvo-cum-indexation models, the lagged inflation term is endogenously generated in a forward-looking framework - since price stickiness arises from both the size and frequency of price adjustments, current price depends on lagged price twice and, hence, a lagged inflation term is endogenously generated from the optimizing behavior of the firms. Thus, the combination of incomplete and infrequent price adjustment generates the lagged inflation term without introducing backward-looking firms. Firms remain forward-looking and follow an optimizing behavior in our framework. Further, in contrast to the general indexation models and sticky information models, prices are not continuously adjusted in the proposed model. The new Phillips curve

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<sup>2</sup>See, e.g., Gregory N. Mankiw and Ricardo Reis (2002), Christiano, Lawrence J. Martin Eichenbaum, Charles L. Evans (CEE 2005) and Frank Smets and Rafael Wouters (2003, 2007). Notice that continuously price updating is an implication of many other New Keynesian models including Mankiw and Reis (2002), Rotemberg (1982), Sharon Kozicki and Peter A. Tinsley (2002), among several others.

<sup>3</sup>See, e.g. Peter J. Klenow and Oleksiy Kryvtsov (2008), Luis J. Alvarez, Emmanuel Dhyne, Marco M. Hoeberichts, Claudia Kwapil, Herve Le Bihan, Patrick Lunnemann, Fernando Martins, Roberto Sabbatini, Harald Stahl, Philip Vermeulen, and Jouko Vilmunen (2006), Luis J. Alvarez (2008), Peter J. Klenow and Benjamin A. Malin (2010), Martin Eichenbaum, Nir Jaimovich, and Sergio Rebelo (2008), etc. In addition, Alan S. Blinder, Elie R. D. Canetti, David Lebow, and Jeremy B. Rudd (1998) and Mark J. Zbaracki, Mark Ritson, Daniel Levy, Shantanu Dutta, and Mark Bergen (2004) provide micro-evidence for variable costs, including managerial and customer costs. International evidence is shown in Angeloni et al. 2006, Alvarez 2008, Emi Nakamura and Jon Steinsson 2008, Mark Bills, Peter J. Klenow, and Benjamin A. Malin 2012, Klenow and Malin 2010, among several others.

based on dual stickiness nests the standard NKPC as a special case (Calvo pricing or quadratic cost) and offer an alternative to the ad-hoc hybrid NKPC and the sticky information Phillips curve.

Additionally, the new sticky inflation model has different policy implications from the indexation models. While the indexation models imply that price dispersion is proportional to a change in the inflation rate due to the counterfactual assumption of continuous price adjustments, the proposed model implies that price dispersion is proportional to the inflation rate. In addition, the proposed model is appropriately designed for policy analysis since all firms are forward-looking and follow an optimizing behavior. Our sticky inflation model nests the standard NKPC as a special case (Calvo pricing) and offers an alternative to the hybrid NKPC.

Our small-scale dynamic stochastic general equilibrium (DSGE) model is estimated using Bayesian techniques. Empirical results indicate strong evidence of incomplete and infrequent price adjustment, based on the parameter estimates, supporting the proposed model. The model provides a theoretical foundation on inflation inertia which, in turn, has an important role in enhancing the goodness-of-fit of the model. In addition, the estimates closely match extensive microdata evidence regarding the frequency and size of price adjustment. In particular, we find that the model has the ability to generate small and even large price changes observed from microdata. The reason is that the introduction of incomplete price adjustment in a staggered price contracts model leads to an amplification of the impact of cost-push shocks on inflation (large price changes) and a reduction of the response of inflation to demand and monetary shocks (small price changes). In contrast to our model, the Calvo model implies that firms make large price adjustments in response to demand and monetary shocks and small price adjustments in response to cost shocks.

Our results also show that the our model produces relatively more frequent small price changes than models based on the standard Calvo pricing, consistently with microeconomic evidence. Klenow and Kryvtsov (2008) document that the Calvo model fails to generate as many small price changes as observed in the microdata collected for the Consumer Price Index (CPI). On the other hand, our simulation exercise shows that extensions of the Calvo pricing model such as the hybrid NKPC of Christiano et al. (2005) and models based on the quadratic adjustment cost of Rotemberg (1982) generate small price adjustments due to the assumption of continuous price adjustments.

We document evidence that our model performs very well in matching the frequency of price changes reported from microdata studies. The average length of time between price changes is estimated to be between 9.0 and 12.5 months. Eichenbaum, Jaimovich and Rebelo (2008) find that firms change prices only every 11.1 months. Klenow, and Malin (2010) find that that the weighted median duration of reference prices is 10.6 months. In contrast, for Calvo model, in which prices are completely adjusted to the optimal level at discrete time intervals, the average duration of price contracts is estimated to be about two years. This paper shows that the introduction of incomplete price adjustment into a staggered price contracts setting leads to smaller response of prices to changing economic conditions (flatter Phillips curve) and, as a consequence, only a moderate degree of price rigidity (in terms of frequency of price changes) is required to explain inflation dynamics.

Another result is that the new sticky inflation model implies a delayed and gradual response of

inflation to a monetary policy shock, which is in accord with the persistence in inflation observed in the data. It is well-known in the literature that the baseline NKPC with Calvo pricing fails to generate a hump-shaped response of inflation to a monetary policy shock, as inflation falls instantly in response to this shock, displaying no inertia. By contrast, in the proposed model the policy shock raises interest rate and, thus, has a negative impact on inflation and output gap, generating a delayed response of inflation due to the incomplete and infrequent price adjustments.

Regarding the observed relation between inflation and output gap, the baseline NKPC with Calvo pricing fails to generate the observed low contemporaneous correlation between current output gap and inflation. Our simulation exercise shows that the assumption that firms are able to adjust prices completely in response to changes in economic conditions leads to an unrealistically high correlation between the two variables. The introduction of incomplete price adjustment into a staggered price contracts setting works to reduce the impact of demand-side shocks on prices, leading to a reduction in the high positive correlation coefficient.

Finally, we uncover evidence on the importance of incomplete price adjustments in generating the observed cross-correlation between inflation and the output gap. John B. Taylor (1999) considers their ability to generate the “reverse dynamic” cross-correlation between output gap and inflation as a yardstick of a success of monetary models.<sup>4</sup> Accordingly, the proposed model yields the “reverse dynamic” result that current output gap tends to be positively related with future inflation, whereas past inflation tends to be negatively associated with current output gap. This paper shows that the introduction of incomplete price adjustment in a staggered price setting plays a crucial role in generating the reversed dynamic correlation between output gap and inflation. The delayed response of inflation to a change in economic activity is a consequence of incomplete and infrequent price adjustment.

The remainder of this paper is organized as follows. Section 2 derives the new sticky inflation model. Section 3 introduces the associated small-scale dynamic general equilibrium model. Section 4 reports empirical and simulation results, and Section 5 concludes.

## 2 Firms’ Problems and the Phillips Curve

We assume that the economy has two types of firms: a representative final goods-producing firm and a continuum of intermediate goods-producing firms.

### 2.1 The Final Goods-Producing Firm

The final goods-producing firm purchases a continuum of intermediate goods,  $Y_{it}$ , at input prices,  $P_{it}$ , indexed by  $i \in [0, 1]$ . The final good,  $Y_t$ , is produced by bundling the intermediate goods

$$Y_t = \left[ \int_0^1 Y_{it}^{1/\lambda_f} di \right]^{\lambda_f} \quad (1)$$

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<sup>4</sup>It is well-known that the labor income share version of the hybrid NKPC is able to explain the observed joint dynamic correlation between inflation and output gap (Smets and Wouters 2007). However, Rudd and Whelan (2007) point out that the U.S. data show that output gap is negatively correlated to labor’s share of income. In this respect, we study whether our model employing output gap is able to explain the observed joint dynamic correlation.

where  $1 \leq \lambda_f < \infty$ . The final goods-producing firm chooses  $Y_{it}$  to maximize its profit in a perfectly competitive market taking both input ( $P_{it}$ ) and output prices ( $P_t$ ) as given. The objective of the final goods-producing firm is expressed as

$$P_t \left[ \int_0^1 Y_{it}^{1/\lambda_f} di \right]^{\lambda_f} - \int_0^1 P_{it} Y_{it} di \quad (2)$$

subject to the technology described in (1). The first order condition of the final-goods-producing firm implies that

$$Y_{it} = \left( \frac{P_{it}}{P_t} \right)^{-\lambda_f/(\lambda_f-1)} Y_t \quad (3)$$

where  $\lambda_f/(\lambda_f - 1)$  measures the constant price elasticity of demand for each intermediate good. The relationship between the prices of the final and intermediate goods can be obtained by integrating (3),

$$P_t = \left[ \int_0^1 P_{it}^{1/(1-\lambda_f)} di \right]^{1-\lambda_f}. \quad (4)$$

Equation (4) is derived from the fact that the final goods-producing firm earns zero profits. The final good price can be interpreted as the aggregate price index.

## 2.2 The Intermediate Goods-Producing Firm

As seen in the literature, the NKPC is most commonly derived using Calvo's (1983) staggered price setting in which a fraction  $(1 - \theta)$  of firms reset prices to optimize profit while the remaining firms maintain their prices unchanged in any given period. In the Calvo economy, as implied by equation (4), the aggregate price level evolves according to

$$P_t = \left[ (1 - \theta) \tilde{P}_{it}^{1/(1-\lambda_f)} + \theta P_{t-1}^{1/(1-\lambda_f)} \right]^{1-\lambda_f} \quad (5)$$

where  $\tilde{P}_{it}$  denotes the optimal price set by the intermediate good-producing firms. The fraction of firms that reoptimizes their prices at time  $t$  choose the same price in equilibrium, thus  $\tilde{P}_{it} = \tilde{P}_t$  for all  $i$ .<sup>5</sup> Since individual prices are optimized in a staggered manner, the aggregate price level evolves sluggishly, making the aggregate price depend on its own lag.

Another popular way of introducing nominal rigidities is to assume that firms face variable costs when changing their prices. Rotemberg (1982) proposes that firms face quadratic costs of price adjustment. Several dimensions of managerial and customer relations may imply that the costs of price adjustment is proportional to its size. Since these costs increase with the magnitude of price adjustment, firm's ability to fully adjust prices could be constrained, making the aggregate price sticky with respect to the size of price changes. We assume that each intermediate goods-producing firm faces the quadratic price adjustment cost given by

$$QAC = \frac{c}{2} \left( \frac{\tilde{P}_t}{P_t} - \frac{\tilde{P}_{t-1}}{P_{t-1}} \right)^2 Y_t \quad (6)$$

<sup>5</sup>See e.g. Michael Woodford (1996) and Tack Yun (1996).

Equation (6) implies that it is costly for current individual price to deviate from past price level, which makes price sticky. The cost of adjusting prices is zero when there is no change in real price. In this setup, consumers are likely to accept price changes proportional to the inflation rate, which could be perceived as fair, and could be associated with less consumers' antagonism.<sup>6</sup>

Zbaracki et al. (2004) document quantitative and qualitative evidence that managerial and customer costs of price adjustment are convex using data from a large U.S. industrial manufacturer, as quoted below:

*“The managerial costs of price adjustment increase with the size of the adjustment because the decision and internal communication costs are higher for larger price changes. The larger the proposed price change, the more people are involved, the more supporting work is done, and the more time and attention is devoted to the price change decisions. ... Customer costs of price adjustment also increase with the size of the adjustment because larger price changes lead to both higher negotiation costs and higher communication costs. ... Given the convexity of the price adjustment costs, pricing managers often felt it was not worth the fight to make major changes, and would propose smaller ones.”* (Zbaracki et al. 2004 p. 524)

Their findings indicate that the managerial costs and the customer costs are, respectively, 6 and 20 times greater than the menu costs. Although the company investigated by Zbaracki et al. (2004) faces the convex costs of price adjustment, it does not change prices continuously as implied by Rotemberg's sticky price model:

*“We can't change prices biannually, it is not the culture here.”- Pricing manager*” (Zbaracki et al. 2004 p. 525)

The company's infrequent price adjustment can be explained by implicit contract theory. Fabiani et al. (2005) surveyed around 11,000 firms in the Euro area and found that implicit and explicit contracts theories ranked first and second among the explanations of price stickiness. In sum, the company investigated by Zbaracki et al. (2004) adjusts its prices annually, but incompletely due to convex costs of price adjustment.

Both the Calvo pricing and the quadratic cost of price adjustment are similar modeling devices in the sense that they lead to sticky prices. However, they yield different implications with respect to the frequency and size of price adjustment. While the Calvo model is associated with the frequency of price changes, the quadratic price adjustment cost is related to the magnitude of price changes. These pricing models are closely associated with the decision problems faced by firms, regarding when and by how much to change prices. The Calvo pricing is designed to capture infrequent price adjustments that arise from implicit and explicit contracts, coordination failure, and fixed costs of changing prices.<sup>7</sup> On

<sup>6</sup>The ability of the proposed model to generate inflation persistence does not depend on the specification of price adjustment costs. Replacing the quadratic adjustment cost function with the one based on nominal cost instead, as in Rotemberg (1982), yields a very minor change in our model as well as in the NKPC. Once the price adjustment cost function is specified as the form of Equation (6), the Phillips curve can be written as  $\hat{\pi}_t = E_t \hat{\pi}_{t+1} + \frac{\alpha-1}{\beta c} \hat{m}c_t$ , whereas adopting  $(c/2) (\tilde{P}_t - \pi \tilde{P}_{t-1})^2 Y_t$  results in  $\hat{\pi}_t = \beta E_t \hat{\pi}_{t+1} + \frac{\alpha-1}{c} \hat{m}c_t$ . When  $\beta = 1$ , the two models are equivalent.

<sup>7</sup>Blinder et al. (1998) document evidence that the theory of coordination failure ranked first in the United States as the main reason for infrequent price changes. As Nakamura and Steinsson (2013) point out,<sup>7</sup> coordination failure in price setting has two essential elements. First,

the other hand, the Rotemberg pricing is closely related to variable costs such as managerial costs (information gathering and decision making costs), customer costs (negotiation and communication costs), and manager's "fear of antagonizing customers" (Rotemberg 1982, 2005, Zbaracki et al. 2004). It is worth emphasizing that firms face variable costs of price adjustment only when they decide to change prices. Evidence on these frictions are extensively found in the literature as in Zbaracki et al. (2004), and in the surveys by Blinder et al. (1998) or Fabiani et al. (2005).

The intermediate goods-producing firm maximizes real profit from selling its output in a monopolistically competitive goods market assuming that its price is fixed with the Calvo probability  $\theta$  in any given period. Additionally, the firm faces the quadratic cost of adjusting its price. The firm chooses  $\tilde{P}_t$  to maximize

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[ \frac{(\tilde{P}_t - mc_{t+k} P_{t+k}) Y_{it+k}}{P_{t+k}} \right] - \frac{c}{2} \left( \frac{\tilde{P}_t}{P_t} - \frac{\tilde{P}_{t-1}}{P_{t-1}} \right)^2 Y_t \quad (7)$$

subject to the demand function described by equation (3).  $mc_t$  represents the real marginal cost of labor. Firm  $i$ 's profit depends on  $\tilde{P}_t$  when it cannot re-optimize its price. The average duration of price contracts is calculated as  $1/(1-\theta)$  in the Calvo economy. When the quadratic cost of price adjustment is assumed to be zero, the model collapses into the standard NKPC in which firms completely adjust their prices whenever they reset them.

Plugging equation (3) into (7) and then rearranging it in terms of the relative price,  $\tilde{p}_t \equiv \tilde{P}_t/P_t$ , yields

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[ (\tilde{p}_t \tilde{X}_{tk} - mc_{t+k}) (\tilde{p}_t \tilde{X}_{tk})^{-a} Y_{t+k} \right] - \frac{c}{2} (\tilde{p}_t - \tilde{p}_{t-1})^2 Y_t \quad (8)$$

where  $\tilde{X}_{tk} \equiv 1/\pi_{t+1}\pi_{t+2}\dots\pi_{t+k}$  and  $a \equiv \lambda_f/(\lambda_f - 1)$ . The first order condition is given by

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[ \tilde{X}_{tk}^{-a} \tilde{p}_t^{-a-1} Y_{t+k} \left( (1-a)\tilde{p}_t \tilde{X}_{tk} + (a)mc_{t+k} \right) \right] - c(\tilde{p}_t - \tilde{p}_{t-1}) Y_t = 0. \quad (9)$$

Log-linearization of the first order condition yields

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[ (\hat{p}_t + \hat{X}_{tk} - \hat{m}c_{t+k}) \right] = \frac{c}{1-a} (\hat{p}_t - \hat{p}_{t-1}) \quad (10)$$

where  $\hat{p}_t$ ,  $\hat{X}_{tk}$ , and  $\hat{m}c_{t+k}$ , denote the log-deviation (denoted by hat) of  $\tilde{p}_t$ ,  $\tilde{X}_{tk}$ , and  $mc_{t+k}$ , from their steady state values, respectively. The equality in equation (10) emerges from the tradeoff between the marginal cost of price adjustment (r.h.s) and the marginal benefit (l.h.s.) from changing prices after taking into account future inflation and real marginal cost. A rise in price has a positive effect on profit, whereas an increase in future inflation and in real marginal cost of labor has a negative impact. The marginal cost of adjusting prices associated with variable costs increases with the size of the price

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pricing decisions are staggered since firms wait for other firms to change their prices. Second, firms that have an opportunity to adjust prices will adjust them partially in response to various shocks because other firms keep their prices unchanged. In this respect, our model shares these essential elements of the theory of coordination failure even though pricing does not depend on the behavior of other firms. The fundamental difference between these two theories emerges from the ability to generate a lagged inflation term in the Phillips curve. We later show that our model is able to generate small and large price changes while, as Klenow and Willis (2006) point out, a model with strategic complementarities based on Kimball (1995) is hard to reconcile with large price changes.



adjustment.

Log-linearizing equation (5) associated with the Calvo pricing yields the following equation:

$$\hat{p}_t = \frac{\theta}{1 - \theta} \hat{\pi}_t. \quad (11)$$

Thus,  $\hat{p}_t - \hat{p}_{t-1} = [\theta/(1 - \theta)][\hat{\pi}_t - \hat{\pi}_{t-1}]$ . Plugging this into equation (10), rearranging the terms, and deleting the hat on the variables for convenience yields

$$\pi_t = \Lambda_f E_t \pi_{t+1} + \Lambda_l \pi_{t-1} + \lambda m c_t \quad (12)$$

where  $\Lambda_f \equiv \eta/\tau$ ,  $\Lambda_l \equiv \kappa/\tau$ ,  $\lambda \equiv (1 - \theta\beta)/\tau$ ,  $\tau \equiv (\theta/(1 - \theta) + (1 + \theta\beta)\kappa)$ ,  $\eta \equiv \theta\beta(1/(1 - \theta) + \kappa)$ ,  $\kappa \equiv c(1 - \theta\beta)\theta/(a - 1)(1 - \theta)$ . If  $\beta = 1$ ,  $\Lambda_f + \Lambda_l = 1$ . Note that the proposed model nests the baseline NKPC model with Calvo setting as a particular case. When the quadratic cost of price adjustment is zero, our model collapses into the baseline NKPC of the form

$$\pi_t = \beta E_t \pi_{t+1} + \frac{(1 - \theta)(1 - \theta\beta)}{\theta} m c_t. \quad (13)$$

The derivation process of the new sticky inflation model reveals how the two sources of price stickiness endogenously generate a lagged inflation term. Partial price adjustments (due to convex cost) in the staggered Calvo price setting imply inflation persistence. This theory shows that, in contrast to the hybrid NKPC, inflation could be persistent even though all firms are forward-looking. Inflation persistence is a consequence of the combination of infrequent and incomplete price adjustment.

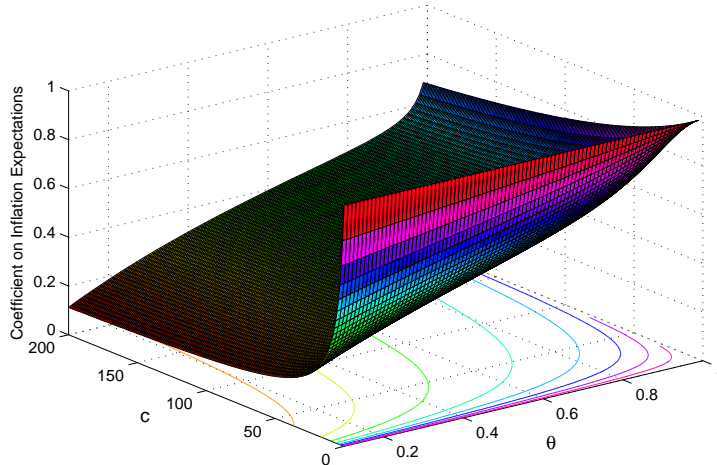
Figure 1 displays how the coefficient on inflation expectations is determined by the Calvo parameter  $\theta$  and the Rotemberg parameter  $c$  associated with the costs of price adjustment. We set the parameter  $a$  that measures the degree of market power of each intermediate goods-producing firm to 6 as in Ireland (2001). The coefficient on inflation expectations  $\Lambda_f$  increases with  $\theta$  and decreases with  $c$ . One interesting property of the model is that as the average duration of price contracts,  $1/(1 - \theta)$ , increases the contribution of inflation expectations to inflation dynamics also increases. This property is different from existing sticky price models in which the coefficient on inflation expectations does not depend on the duration of price spells. The figure also shows that an increase in the value of  $c$  reduces the role of inflation expectations in determining inflation dynamics.<sup>8</sup> An increase of the quadratic price adjustment cost leads to a rise in the coefficient on lagged inflation  $\Lambda_l$  and a decrease in the one on inflation expectations  $\Lambda_f$ , since the presence of price adjustment costs hinders prices from deviating from its previous level. Thus, the shape of the coefficient on lagged inflation is inverse of the one on inflation expectations.

Figure 2 presents the slope of the Phillips curve. An increase in either the Calvo parameter ( $\theta$ ) or the Rotemberg parameter ( $c$ ) reduces the slope of the Phillips curve, since it makes prices less responsive to changes in economic activity or real marginal cost. Embedding the price adjustment costs to the baseline

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<sup>8</sup>This implies that, in sectors where prices are relatively less sticky in terms of the frequency of price adjustment, inflation expectations can still play an important role in determining inflation dynamics as long as the costs of price adjustment is low.

Figure 1: Coefficient on Inflation Expectations



sticky price model further reduces the slope of the Phillips curve. The convex costs of price adjustment slow the response of prices to a change in demand and supply conditions. In this respect, our model shares some properties of the Calvo model combined with strategic complementarity. The presence of strategic complementarity in price setting also diminishes the response of “reset prices”.<sup>9</sup> Eichenbaum and Fisher (2007) show that the combination of staggered price contracts and strategic complementarity results in a plausible degree of price stickiness. Later, we also present estimation results that show that the estimated frequency of price changes is consistent with the findings from microdata studies. The fundamental difference between our model and sticky price models with strategic complementarity is associated with the ability to generate a lagged inflation term that captures inflation persistence.

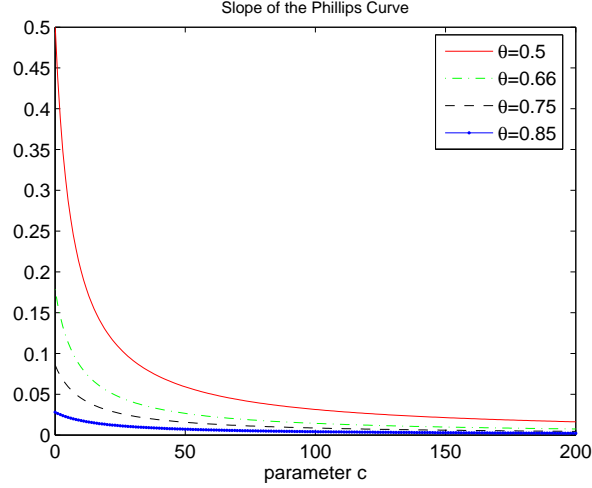
### 3 A Small Scale DSGE Model

We consider a small scale DSGE model consisting of three equations: the IS curve, the Phillips curve, and the Taylor rule. The IS curve is derived from maximizing the expected present discounted value of utility,  $E_t \sum_{k=0}^{\infty} \beta^k \left( \frac{C_{t+k}^{1-1/\sigma}}{1-1/\sigma} - \frac{N_{t+k}^{1+\varphi}}{1+\varphi} \right)$ , subject to the budget constraint,  $C_{t+k} + \frac{B_{t+k}}{P_{t+k}} = \left( \frac{W_{t+k}}{P_{t+k}} \right) (N_{t+k}) + \exp(-\xi_{t+k-1})(1+i_{t+k-1}) \left( \frac{B_{t+k-1}}{P_{t+k}} \right) + \Pi_{t+k}$ , where  $C_t$  is the composite consumption good,  $N_t$  is hours worked,  $\Pi_t$  is real profits received from firms, and  $B_t$  is the nominal holdings of one-period bonds that pay a nominal interest rate  $i_t$ . As in Smets and Wouters (2007), we introduce a risk premium shock,  $-\xi_{t-1}$ , into the DSGE model. The IS curve is given by

$$y_t = E_t y_{t+1} - \sigma(i_t - E_t \pi_{t+1}) + \varepsilon_t^y \quad (14)$$

<sup>9</sup>Bils, Klenow and Malin (2012) document evidence against strategic complementarity in that reset prices adjust more rapidly than what New Keynesian models with strategic complementarity predict. However, this issue is controversial. Kara (2011) provides evidence that empirical measure of reset inflation by Bils, Klenow and Malin (2012) is different from “the theoretical ideal”, and that a DSGE model with strategic complementarities and heterogeneous firms in price rigidity is able to explain the stylized facts reported in Bils, Klenow and Malin (2012). Gopinath, Itskhoki, and Rigobon (2010) study the behavior of U.S. import and export prices, and find that firms raise prices by 0.25% in response to an 1.0% increase in the cumulative exchange rate, since they have adjusted prices last time. They also find that firms adjust imported prices in response to changes in the exchange rate before the previous price adjustments. The findings are consistent with Fitzgerald and Haller (2012) and Burstein and Jaimovich (2012).

Figure 2: Slope of the Phillips Curve



where  $y_t$  and  $i_t$  denote output gap and the nominal interest rate, respectively. We interpret the disturbance term as a preference shock,  $\varepsilon_t^y \equiv \sigma \xi_t$ , which is assumed to follow an AR(1) process,  $\varepsilon_t^y = \delta_\pi \varepsilon_{t-1}^y + \nu_t^y$  with  $\nu_t^y \sim N(0, \sigma_y^2)$ . The Phillips curve can be written as

$$\pi_t = \Lambda_f E_t \pi_{t+1} + \Lambda_l \pi_{t-1} + \left(\frac{1}{\sigma} + \varphi\right) \lambda y_t + \varepsilon_t^\pi \quad (15)$$

since  $mc_t = (\frac{1}{\sigma} + \varphi)y_t$ . The disturbance term,  $\varepsilon_t^\pi$ , is a cost-push shock, which follows an independently and identically distributed (i.i.d.) process with  $N(0, \sigma_\pi^2)$ .<sup>10</sup> The shock  $\varepsilon_t^\pi$  can be embedded into the model by introducing an exogenous cost component ( $e_t^\pi$ ) in the objective function of firms, which is given by

$$E_t \sum_{k=0}^{\infty} (\theta\beta)^k \left[ (\tilde{P}_t - \exp(e_t^\pi) mc_{t+k} P_{t+k}) Y_{it+k} / P_{t+k} \right] - (c/2) \left( \tilde{P}_t / P_t - \tilde{P}_{t-1} / P_{t-1} \right)^2 Y_t$$

The disturbance term captures fluctuations of inflation driven by an exogenous cost component that are not considered in the model. The shock  $\varepsilon_t^\pi$  can be expressed as a constant times  $e_t^\pi$ .

The monetary authority adjusts the interest rate in response to expected inflation and output as follows

$$i_t = \rho i_{t-1} + (1 - \rho)(\alpha_\pi E_t \pi_{t+1} + \alpha_y y_t) + \varepsilon_t^i \quad (16)$$

where a monetary shock  $\varepsilon_t^i$  follows an i.i.d. process with  $N(0, \sigma_i^2)$ , and  $\rho$  measures the degree of interest rate smoothing in monetary policy. We assume that policy makers are forward-looking in stabilizing inflation. However, they adjust the interest rate in response to current economic activity. The monetary authority's responses to inflation and output are determined by the parameters  $\alpha_\pi$  and  $\alpha_y$ .

<sup>10</sup>The estimated residuals from Equation (15) are plotted in Figure 7. Although we do not report here, diagnostic tests indicate that the estimated residual is not correlated with its first, second, and third lags but to the fourth lag and the MA(1) term. Hence, we check robustness of our results to an alternative ARMA(4,1) shock process in section 4.7.2.

## 4 Empirical Results

### 4.1 Data and Priors

In order to estimate the DSGE model, we employ the output gap measure of the Congressional Budget Office (CBO), the effective Federal Funds rate from the Federal Reserve Bank of Saint Louis, and the implicit GDP deflator from the Bureau of Labor Statistics.

The small scale DSGE model has three shocks; demand, monetary, and cost shocks and three variables; the interest rate, output, and inflation. A technology shock is abstracted from the model, however a cost push shock on the supply side is present. Since there is no variation of technology, the output gap defined as the deviation of output from its potential level is equivalent to output in the model. This approach allows us to estimate the DSGE model with one- and two-sided filtered output as well as the CBO’s output gap measure to test for robustness of our results.<sup>11</sup> As emphasized by Gali and Gertler (1999), the output gap is observed with considerable measurement errors. We consider the the CBO output gap for estimation in the following subsections, and then output detrended using Hodrick–Prescott (HP) two-sided filter and Christiano-Fitzgerald (CF) in Section 4.5.

The data range from 1960:1 to 2008:4. Since the interest rate hits the zero lower bound in 2009:1, our sample ends in 2008:4 to avoid issues related to the zero lower bound and the unusual dynamics during the financial crisis period. The priors on the model parameters are summarized in Table 1. We set the parameter  $a$  to 6. This implies a steady state markup of price over marginal cost of twenty percent, as in Rotemberg and Woodford (1992) and Ireland (2001). We also set  $\beta$  to be 0.99, as commonly assumed in the literature. The parameter  $\varphi$  is set to be 1.5 following the estimate of Gourio and Noulz (2006) using monthly panel data from the National Longitudinal Survey of Youth (NLSY). We estimate the model using Bayesian techniques. We use 100,000 draws to estimate the DSGE model, but only start calculating posterior features after 50,000 draws. The Metropolis-Hastings algorithm is applied to obtain the maximum likelihood estimates.

### 4.2 Estimation Results

Table 1 reports estimation results of the DSGE model. The posterior mean estimates of monetary policy parameters  $\rho$ ,  $\alpha_\pi$ , and  $\alpha_y$  are similar to the ones reported in the literature. The parameter measuring the degree of interest rate smoothing is estimated to be 0.79. The estimate of  $\alpha_\pi$  associated with the Fed’s response to inflation expectations is 1.73, whereas the parameter related to the response of the Fed to the output gap is estimated to be 0.50. The posterior mean of  $\theta$ , the Calvo measure of degree of nominal rigidity, is estimated to be 0.76, which implies that only a quarter of the firms are able to reset their prices to optimize profit while the remaining keep their prices unchanged. The estimate implies that the average length of time between price changes is 4 quarters. The parameter  $c$  is estimated to be 167.3. The parameters associated with both Calvo-type price stickiness and the quadratic price adjustment cost are within the 95% confidence interval. Figure 3 shows the prior and

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<sup>11</sup>Justiniano and Primiceri (2008) show that the “DSGE based output gap captures cyclical fluctuations very well, closely resembling HP-detrended output and the CBO output gap in particular.”

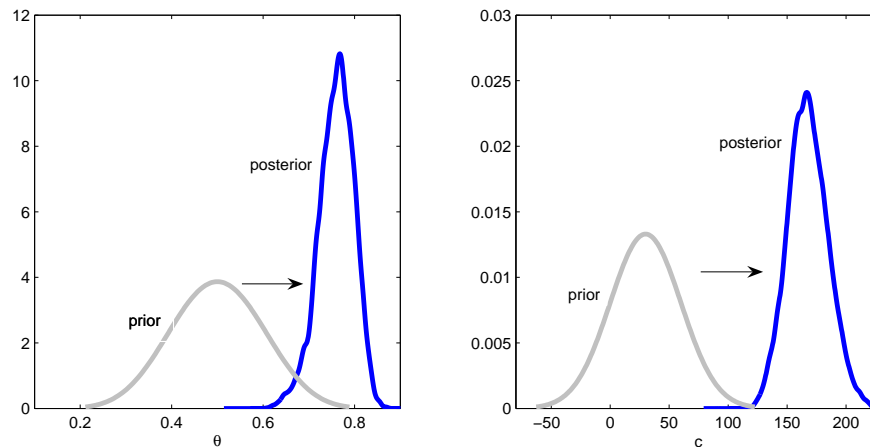
posterior distributions of  $\theta$  and  $c$ . Substantial movements of the posterior distributions away from the prior distributions are observed from the figure. Thus, the null hypothesis of no price rigidities with respect to the frequency and size of price adjustment is rejected, supporting the proposed sticky inflation model.

The finding of the frequency of price adjustment is in accord with microdata evidence that shows there is substantial price stickiness. For example, Eichenbaum, Jaimovich and Rebelo (2008) propose a method to measure sticky reference prices among shorter-lived new prices and find that they change only every 11.1 months. Klenow and Malin (2010) generalize their definition of reference prices for the U.S. CPI and find that that the weighted median duration of reference prices is 10.6 months.<sup>12</sup>

Table 1: Estimation Results - Sticky Inflation DSGE Model: 1960:1-2008:4

parameter	prior dist.	prior mean	prior st. dev.	posterior mean	95% of confidence interval
$\theta$	beta	0.5	0.10	0.76	[0.70, 0.82]
$c$	normal	30	30.0	167.3	[140.0, 195.6]
$\sigma$	invg	1	$\infty$	0.16	[0.13, 0.18]
$\rho$	beta	0.7	0.05	0.79	[0.76, 0.81]
$\alpha_\pi$	normal	1.5	0.25	1.73	[1.60, 1.87]
$\alpha_y$	normal	0.5	0.1	0.50	[0.35, 0.65]
$\delta_y$	beta	0.5	0.2	0.95	[0.93, 0.98]
$\sigma_\pi$	invg	0.1	2	0.70	[0.63, 0.76]
$\sigma_y$	invg	0.1	2	0.16	[0.13, 0.19]
$\sigma_i$	invg	0.1	2	0.99	[0.89, 1.07]

Figure 3: Priors and Posteriors of Key Parameters



Alvarez (2008) investigates firms in 18 countries and finds that prices generally change around once a year with a median of 11.8 months. Alvarez et al. (2006) find that price changes are even less common in the Euro area. On average, in a given month only 15.1 percent of prices change and the average length

<sup>12</sup>The reference price for each UPC as defined by Eichenbaum et al. (2009) corresponds to the modal price in each quarter using weekly price data from a large U.S. supermarket chain. Bills, Klenow, and Malin (2012) define the reference price in each month as the most common price of an item in the 13-month window centered on the current month.

of time between price changes is from 4 to 5 quarters. These figures suggest that price adjustment in the Euro area is less frequent than in the US. These studies focus on the Great Moderation period. Section 4.7 shows that our model implies that the estimated duration of price contracts ranges from 9.0 to 12.5 months for the post-1983 period. Thus, the results from the DSGE model regarding the frequency of price adjustments are in agreement with microdata evidence. On the other hand, results from models that predict continuous price changes such as indexation models and sticky information models cannot be reconciled with the pervasive low frequency of price adjustment observed in every country and across different data sources.

### 4.3 Impulse Response Functions

This section investigates the effect of the adjustment costs of prices on impulse response functions. The impulse response functions are generated using the estimates reported on Table 1, allowing the parameter  $c$  to vary from 0 to its estimated value of 167.3. Figure 4 displays the impulse response functions of inflation, output gap, and interest rate to an one standard deviation cost-push shock (first column), demand shock (second column), and monetary shock (third column).

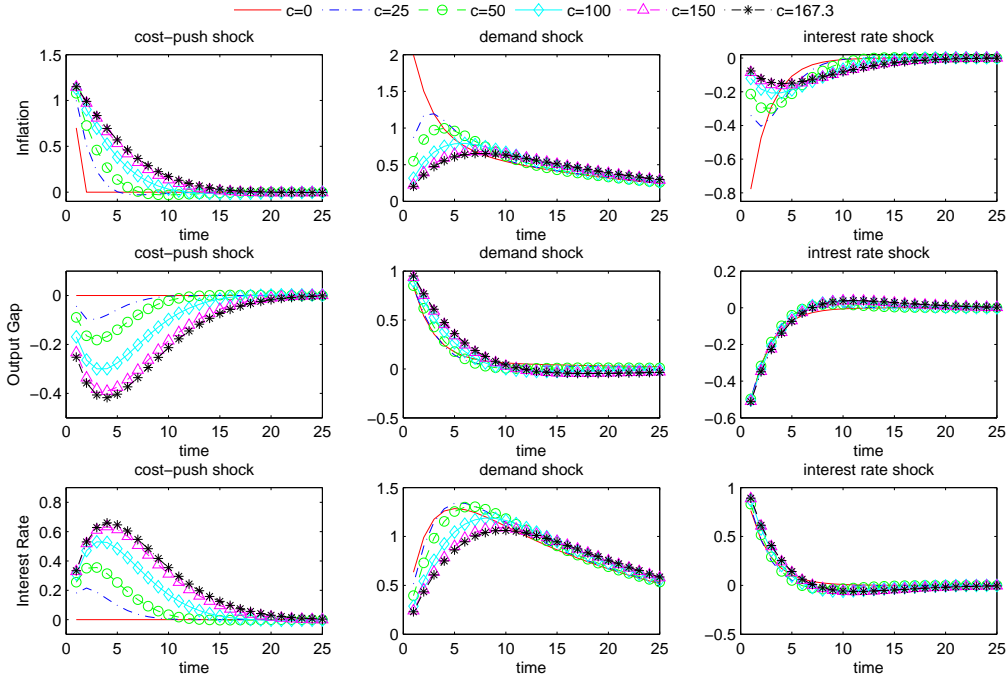
As seen in the first column, the cost-push shock leads to an immediate increase in inflation regardless of the value of  $c$ . However, in contrast with the effect of the cost-push shock in the baseline NKPC ( $c = 0$ ), the response of inflation dies off more gradually as the value of  $c$  increases. Interestingly, the proposed model also differs from the baseline with respect to the response of interest rates and output gap to a cost-push shock: the Federal Reserve raises interest rate in response to higher inflation, which leads to a decrease in the output gap. The largest impact on the output gap is reached after around 3 quarters. On the other hand, interest rates and output gap do not respond to a cost-push shock in the baseline model - since the response of inflation is very temporary, only one quarter, the shock does not affect inflation expectations and, as result, the Federal Reserve does not respond to the shock with a change in interest rate and, thus, output gap does not fall.

The impulse responses to a demand shock are shown in the second column. The shock drives up inflation, output gap, and interest rate. There is a striking difference between the proposed model with convex costs of price adjustment and the baseline with respect to the inflation response. Although prices are sticky in the baseline model, inflation does not exhibit persistence. Thus, the largest impact of the shock on inflation takes place immediately. In contrast, the response of inflation in the proposed sticky inflation model is much more gradual and persistent, with the largest impact occurring 6 quarters later. This result arises from the fact that price setters not only change their prices infrequently, but also do not completely readjust their prices when the opportunity occurs. In the baseline model, as firms fully adjust prices in response to a demand shock, the impact on inflation is large (almost a two-percent increase) and immediate due to the role of expectations in determining inflation. When a positive demand shock hits the economy, firms expect output gap to increase for several quarters. Since inflation is determined only by a discounted sum of current and expected future values of the output gap in the baseline NKPC model, inflation rises substantially in response to the demand shock. However, when

firms face adjustment costs regarding the size of price changes, the impact of inflation expectations on prices reduces sharply, leading to a gradual rather than an abrupt rise in inflation. The delayed and gradual response of inflation to a change in the output gap is an interesting consequence of the proposed model, which considers both infrequent and incomplete price adjustment.

The third column shows the estimated impact of a one-standard deviation contractionary monetary policy shock. It is well-known in the literature that the baseline NKPC fails to generate a hump-shaped response of inflation to a monetary policy shock. The policy shock raises interest rate and, thus, has a negative impact on inflation and output gap. The baseline NKPC model predicts that inflation falls instantly in response to this shock, displaying no inertia. By contrast, there is a delayed and gradual response of inflation to the policy shock in the proposed model. The largest impact on inflation occurs after 4 quarters. Thus, the new sticky inflation model is more in accord with the persistence in inflation as observed in the data. The delayed response of inflation can, once again, be explained by incomplete and infrequent price adjustments.

Figure 4: Impulse Response Functions



### 4.4 Dynamic Correlation Between the Output Gap and Inflation

Taylor (1999) stresses that the ability to characterize the “reverse dynamic” relationship between the output gap and inflation is a criterion for the success of monetary models. This section examines whether the estimated model is able to generate the observed dynamic correlation between inflation and output gap, and the role of incomplete price adjustments in a staggered price setting.<sup>13</sup>

<sup>13</sup> Although the hybrid NKPC model with labor’s share of income as a proxy of real marginal costs is able to explain the observed dynamic correlation (e.g., Smets and Wouters 2007), this is not the case when output gap is used instead. In fact, Rudd and Whelan (2007) point out

Figure 5 displays the dynamic correlation between inflation and output gap generated from the estimated proposed DSGE model (blue line) and the estimated baseline DSGE model (dash-dot line with squares), as well as the *observed* dynamic correlation between inflation and output gap measures (line with circles) for comparison. The top (bottom) panel presents results based on the CBO (HP) output gap. As highlighted by Gali and Gertler (1999), observed current output gap tends to be positively related with future inflation, whereas past inflation tends to be negatively associated with current output gap. As seen in Figure 5, our DSGE model performs very well in replicating the observed dynamic correlation between inflation and output gap regardless of output gap measures. On the other hand, the model-implied dynamic correlation changes substantially when the quadratic price adjustment cost is restricted to zero - the baseline NKPC model fails to predict the observed reverse dynamic correlation since it implies that lagged inflation is positively associated with current output gap. In addition, the contemporaneous correlation between these series implied by the baseline model is abnormally high, in contrast to the actual data. This evidence indicates that the assumption of incomplete price adjustments is important in accounting for the output-inflation dynamics.

We investigate this issue further in Figure 6, which shows the contribution of each shock and of convex costs of price adjustment to the dynamic correlation between output gap and inflation. The top and bottom panels are obtained using the estimates of the DSGE model reported in Table 1. The top panel is generated by feeding the sequence of innovations in each shock into the DSGE system with the parameter  $c$  fixed at its posterior mean of 167.3, while the bottom panel by allowing this parameter to vary from 0 to 167.3.

The top panel indicates that demand (dash-dot line with pluses) and monetary (dash-dot line with asterisks) shocks yield a positive contemporaneous correlation between the two variables, whereas cost-push shocks (line with triangles) produce a negative contemporaneous correlation. Once these shocks are taken into account simultaneously, the implied correlation from the proposed DSGE model (line with circles) matches the observed weak, but still positive, contemporaneous correlation between output gap and inflation.

The bottom panel shows that an increase in the quadratic price adjustment cost lowers the contemporaneous correlation between output gap and inflation. The intuition behind this result is that the increased cost of price adjustment causes a slow and gradual response of inflation to demand and monetary shocks, which leads to substantial movements in output gap, as shown in Figure 4. This in turn yields a relatively weak positive contemporaneous correlation between inflation and output gap.

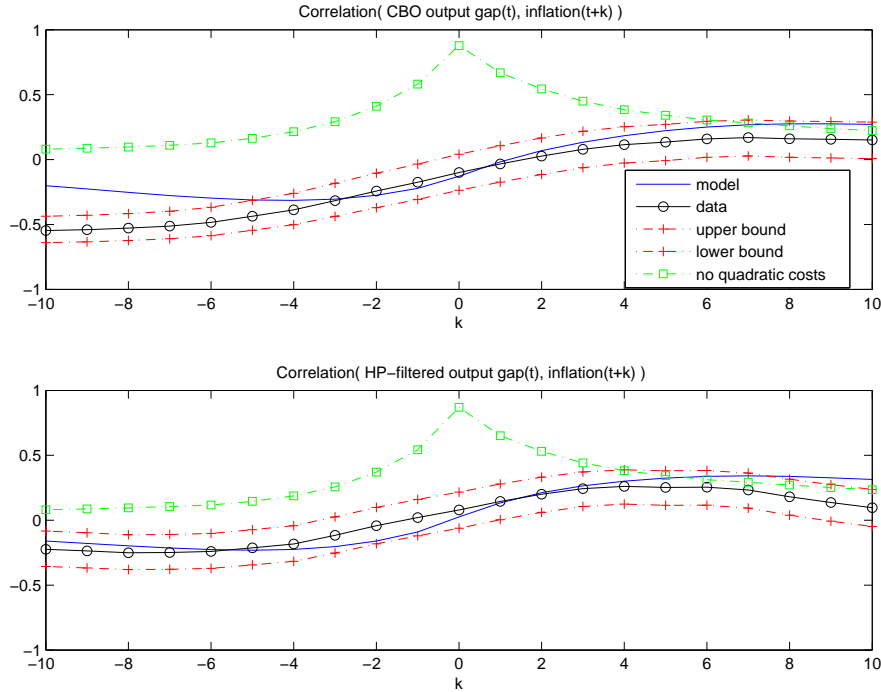
Figure 4 shows that the baseline NKPC model generates relatively large price and output changes in response to demand and monetary shocks and relatively small response to cost shocks. Hence, these demand and monetary shocks dominate cost shocks in determining the correlation between output gap and inflation. As a consequence, this model predicts an unrealistically high positive contemporaneous correlation. Our simulation exercise reveals that implied relatively small price changes to demand-side shocks are important features for the model to be successful in matching the observed contemporaneous

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that the labor income share shows a countercyclical pattern with output gap.



Figure 5: Dynamic Correlation Between the Output Gap and Inflation



correlation.<sup>14</sup>

Figure 6 shows that the maximum correlation between current output gap and future inflation as a response to demand shocks (monetary shocks) occurs after five (three) quarters.

When a positive demand shock (or an expansionary monetary shock) hits the economy, forward-looking firms expect that future values of output gap will be positive for a considerable time. Therefore, firms that receive a random signal of price adjustment raise their prices. The impact of this expectation channel on prices is substantial in the baseline NKPC model in which prices are fully adjusted. By contrast, the demand (or monetary) shock has a limited impact on prices in our sticky inflation model in which prices adjust slowly.

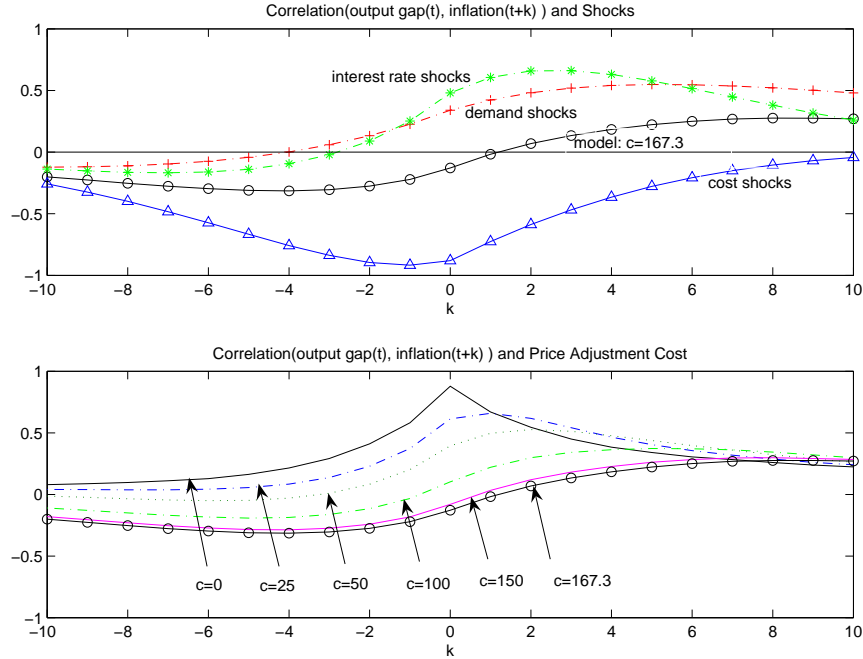
## 4.5 Models Comparison

Table 2 shows the likelihood estimates from the proposed DSGE model with staggering pricing and quadratic price adjustment cost and from the baseline DSGE model ( $c = 0$ ), using CBO, HP (two-sided filter), and CF (one-sided filter) output gap measures. The proposed DSGE model has substantially larger likelihood values relatively to the ones from the baseline model, for any output gap measures.

The estimates of the Calvo parameter  $\theta$  from the proposed model imply that the average length of time between price changes is, respectively, 10.7, 11.1, and 12.5 months for the CBO, HP, and CF output gap measures. The estimated frequency of price changes is consistent with microdata evidence, as

<sup>14</sup>Gagnon and López-Salido (2014) report microeconomic evidence that observed price changes to large demand shocks from U.S. supermarkets are small.

Figure 6: Convex Costs and Dynamic Correlation



discussed above. On the other hand, the average length of time between price changes is substantially higher for the baseline model, 20.0, 25.0, and 27.3 months for the CBO, HP, and CF output gaps, respectively.

The proposed model outperforms the baseline NKPC in explaining the data and matching the frequency of price changes. The introduction of incomplete price adjustment into a staggered price setting implies two sources of price stickiness, and leads to a reduction in the slope of the Phillips curve (the parameter  $\lambda$  in equation 15). Thus, the model can match the data with a relatively smaller degree of price rigidity with respect to the frequency of price adjustment ( $\theta$ ), given that adjustment costs also contribute to a smaller slope of the Phillips curve. On the other hand, when the quadratic price adjustment cost is zero in the baseline model, the Calvo parameter is estimated to be unrealistically high so as to match the observed low slope of the Phillips curve. Our findings show that the assumption of incomplete price adjustment plays a crucial role in matching the observed frequency of price adjustment.

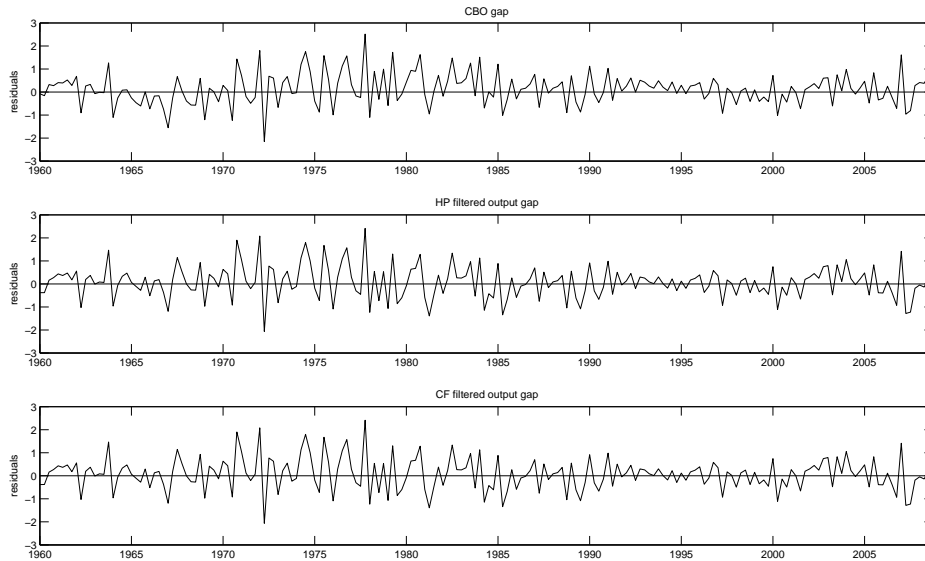
Table 2: Likelihood Estimates (1960:1-2008:4)

gap	Proposed Model			Baseline ( $c = 0$ )	
	likelihood	$c$	$\theta$	likelihood	$\theta$
CBO	-922.3	167.3 ( 140.0, 195.6)	0.76 ( 0.70, 0.82)	-1119.8	0.89 (0.87, 0.91)
HP	-879.1	121.7 (97.4, 146.3)	0.72 (0.63, 0.79)	-1025.8	0.85 (0.83, 0.88)
CF	-836.3	127.0 (102.5, 152.3)	0.73 (0.66, 0.81)	-1008.3	0.88 (0.86, 0.90)

Figure 7 exhibits estimated residuals from the proposed sticky inflation model using the CBO, HP,

and CF output gap measures. The figure shows no serial correlation in residuals, indicating the model works well in capturing systemic patterns of the data. This finding is confirmed by the i.i.d. Q (linear) and Brock, Dechert, Scheinkman and LeBaron (BDS 1996) (nonlinear) tests.<sup>15</sup> We also consider an alternative specification of the cost-push shock to check for robustness of the results in Section 4.7.2.

Figure 7: Residuals



## 4.6 Size of Price Adjustments

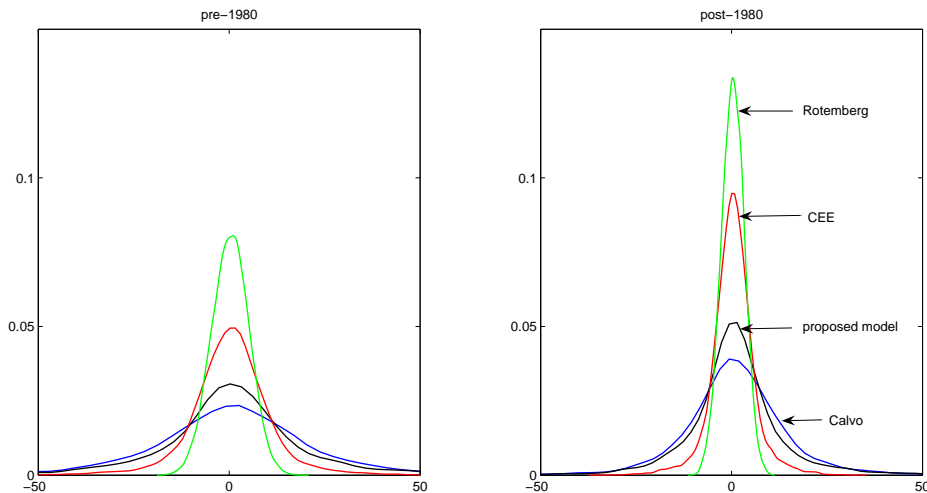
Alvarez et al. (2014) document evidence on small and large price changes from the CPI in France and in the U.S., after correcting for measurement error. This section investigates whether the proposed sticky inflation model has the ability to generate small and large price changes. We also explore how our model is different from other sticky price models such as Christiano, Eichenbaum, and Evans (CEE 2005), a DSGE model with Rotemberg pricing (adjustment cost of price changes but no Calvo pricing), and the Baseline DSGE model (with Calvo pricing but no adjustment cost). The models are compared with respect to their implied distribution of price changes, i.e., the ability to generate small and large price changes.

Figure 8 exhibits the model-implied distributions of price changes before (left panel) and after 1980 (right panel). The distributions of the pre-1980 period have fatter tails compared to the ones from the post-1980 Great Moderation period. Relatively large shocks and loose monetary policy that were present in the pre-1980 period are likely to have contributed to more large price changes during this time. Not surprisingly, the figure shows that the Rotemberg and CEE models generate more small price changes compared to the other models. The CEE model produces more large price changes than the Rotemberg

<sup>15</sup>These results are consistent with those of Cho and Moreno (2006) and Roberts (2006) that employ an output gap-based hybrid NKPC for inflation dynamics. In particular, Roberts (2006) investigates whether the residuals from the this model are serially correlated and finds that the autocorrelation coefficient is negative rather than positive, and that a moving average process is a best fit for the residual. He also finds that “allowing explicitly for serial correlation in the error term of the standard model does not replace the need for lags.”

model because the former allows a fraction of firms to optimize prices in a staggered manner even though prices are adjusted every period. The figure also shows that the proposed sticky inflation model produces more small price changes than the Baseline NKPC and fewer small price changes than the CEE model. Even though both the CEE model and our model are designed to generate inflation persistence, there is a fundamental difference between the models with respect to the size of price changes.

Figure 8: Distribution of Price Changes: Subsample Analysis



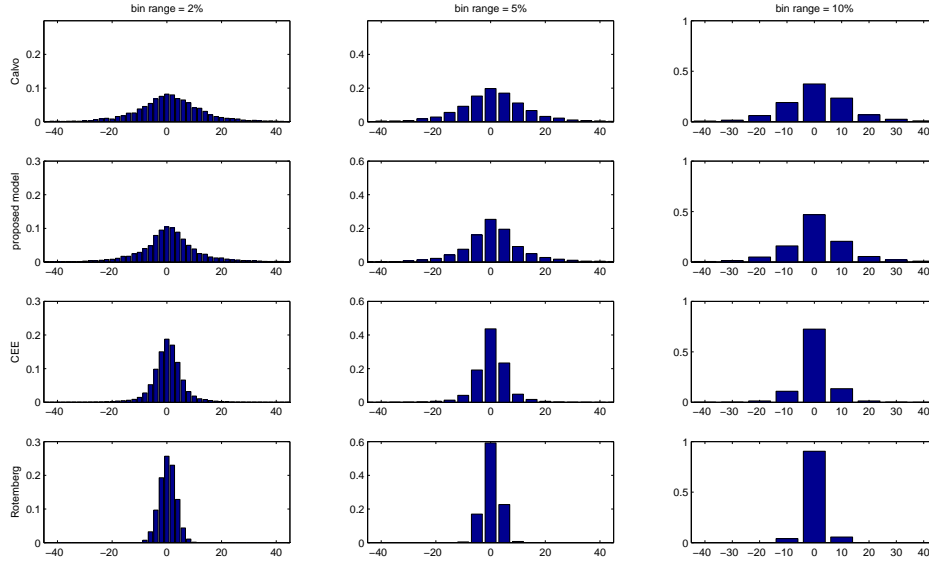
Notes: Subsample estimates of  $\theta$  and  $c$  from Table 4 are used for the proposed model. The CBO output gap measure is adopted to estimate the proposed model. The value of  $c$  is chosen for the Rotemberg model to have the same slope as the baseline NKPC. The remaining parameters and standard deviations of shocks are set at the same values across models.

Figure 9 displays the histograms of price changes of four different models for the post-1983 period. Our model (second row) implies that 47 percent of price changes in absolute value are smaller than 5 percent, 25.0 percent are smaller than 2.5 percent, and 11 percent are smaller than 1 percent, while the Baseline model (first row) predicts that 38 percent of price changes are smaller than 5 percent, 20.0 percent are smaller than 2.5 percent, and 8 percent are smaller than 1 percent. The results regarding the ability of the Baseline model to generate small price changes are similar to those reported in Woodford (2009), in which the Calvo model predicts that 42 percent of price changes are less than 5 percent. Our findings reveal that both the Baseline model and our model are successful in generating many small price changes as observed in microeconomic data.<sup>16</sup>

In the CEE model (third row) 73 percent of price changes are smaller than 5 percent, and in the Rotemberg model (forth row) 90 percent are smaller than 5 percent in absolute value. Most of the price changes are very small in the CEE and Rotemberg models, consistent with their implication that prices are adjusted continuously. The CEE and Rotemberg models predict that the average size of price changes is 4.07 and 2.40, respectively. This simulation exercise reveals that the CEE and Rotemberg

<sup>16</sup>The general empirical finding is that many price changes are smaller than the size of aggregate inflation (see e.g. Dhyne et al. 2005, Alvarez et al. (2006), Klenow and Kryvtsov 2008, etc.) More specifically, Klenow and Kryvtsov (2008) show that in the U.S. 44 percent of consumer price changes are smaller than 5 percent, 25 percent are smaller than 2.5 percent, and 12 percent are smaller than 1 percent, in absolute value. Vermeulen et al. (2007) study the Euro area and find that a quarter of producer price changes is smaller than 1 percent in absolute value, and that the mean price change is only 4 percent. Eichenbaum et al. (2014) emphasize that many small price changes are associated with measurement error. On the contrary, Alvarez et al. (2014) document evidence on small and large price changes from the CPI in France and the US after correcting for measurement error.

Figure 9: Distribution of Price Changes: Histogram



Notes: The distributions are generated using the subsample estimates of the DSGE model. The sample period is from 1983:1 to 2008:4. The CBO output gap measure is adopted to estimate the model. The value of  $\theta$  is set at 0.72 in the Calvo, CEE, and our models. The value of  $c$  is 146.162 in our model. The value of  $c$  is chosen for the Rotemberg model to have the same slope as the baseline NKPC. It results in  $c = 43.2$ . The remaining parameters and standard deviations of shocks are set at the same values across models.

models fall short in matching the average size of price changes observed in microeconomic data. Klenow and Kryvtsov (2008) report that a mean (median) change in regular prices is 11 percent (10 percent) in absolute value. Nakamura and Steinsson (2008) report a median size of 7.7 percent for U.S. finished goods producer prices. In the Euro area, Dhyne et al. (2005) present that the average value of consumer price decrease (increase) is 10 percent (8 percent).<sup>17</sup> The results corroborate the importance of infrequent price adjustment in generating large price changes.

The proposed sticky inflation model produces slightly more small price changes than the Baseline model, but delivers a comparable performance in generating small and large price changes. Interestingly, the proposed model is able to generate even large price changes although the convex cost of price adjustment is embedded in the Baseline model. As discussed before, the combination of staggered price contracts and convex costs amplifies the impact of cost-push shocks to inflation while it reduces the response of inflation to demand and monetary shocks. Thus, cost-push shocks produce large price changes, whereas demand and monetary shocks generate small price changes. This is reason behind the ability of the proposed model in generating large price changes. In contrast to the proposed model, the Baseline model creates large price adjustments in response to demand shocks and small price adjustments in response to cost shocks.

## 4.7 Robustness of the Results

This section reports subsample estimates of the key parameters of the DSGE model to examine

<sup>17</sup>The simulation exercise based on the post-1980 period shows that the average value of price changes in absolute value is 8.6 percent in our model and 9.9 percent in the Calvo model.

whether our results are sensitive to sample period. We also explore whether the results are robust to alternative output gap measures and an alternative cost-shock process.

The sub-sample estimates of the DSGE model are reported in Table 3, for the subsample periods from 1960Q1 to 1979Q4 and from 1983Q1 to 2008Q4. Three different output gap measures are used for estimation: the CBO, and the output gap detrended using HP and CF.

We find that the estimate of  $\theta$  does not change much across sub-samples and output gap measures. It is estimated to be 0.69~0.73 for the pre-1979 period and 0.69~0.72 for the post-1983 period. On the other hand, the parameter associated with quadratic adjustment cost  $c$  is estimated to be a bit higher in the post-1983 era: 98.5~117.5 for the first sample and 110.7~143.5 for the second sample. However, the subsample estimates of  $c$  are not statistically different from each other, as the 95% confidence intervals overlap. The estimates of  $c$  are also not statistically sensitive to output gap measures as 95% confidence intervals also overlap. Overall, the presence of infrequent and incomplete price adjustment is again confirmed by the data, showing that our results are not sensitive to subsamples or output gap measures.

Table 3: Sticky Inflation DSGE Model: Subsample Estimates under Different Measures of Output Gap

gap	1960-1979			1983-2008		
	likel.	$c$	$\theta$	likel.	$c$	$\theta$
CBO	-399.2	117.5 ( 89.4, 149.4)	0.73 ( 0.65, 0.82)	-407.5	143.5 ( 112.3, 173.9)	0.72 (0.64, 0.81))
HP	-384.3	83.8 (55.6, 107.0)	0.68 (0.58, 0.79)	-379.2	110.7 (78.6, 138.5)	0.69 (0.58, 0.79)
CF	-370.4	98.5 (70.8, 129.8)	0.69 (0.59, 0.79)	-368.8	111.4 (80.4, 140.0)	0.69 (0.59, 0.80)

We also investigate whether an alternative specification of a cost-push shock alters our results. In the previous sections we assumed that the cost-push shock follows an i.i.d. process. Residual tests indicate that current residual is not positively correlated to its first, second, and third lags, but it is correlated to the fourth lag and the MA(1) term. Thus, we consider an ARMA(4,1) specification of the cost-push shock process,  $\varepsilon_t^\pi = \sum_{k=1}^4 \rho_k \varepsilon_{t-k}^\pi + v_t^\pi - \delta v_{t-1}^\pi$ . We assume that the prior distribution of  $\rho_k$  is a Normal distribution with mean zero and standard deviation 0.1 for  $k \in [1, 2, 3, 4]$  and the prior distribution of  $\delta$  is a Beta distribution with mean 0.5 and standard deviation 0.2. The estimation results are shown in Table 4. When the cost-push shock is assumed to follow an i.i.d. (or an ARMA(4,1)) process, the marginal likelihood is -922.3 (or -906.1), -879.1 (or -867.3), and -836.3 (or -824.8) for the CBO, HP, and CF output gap measures, respectively. The alternative shock process for residuals increases the likelihood only slightly but there is no significant difference between the marginal likelihoods using Bayes factors.

The estimates of  $c$  range from 127.0 to 167.3 with the i.i.d. process and from 117.7 to 140.1 with the ARMA(4,1) process. The estimated frequency of price adjustment is quite similar to those reported in previous sections. The estimates of  $\rho_1$  are either statistically zero or low. These results confirm the findings of Robert (2006) that a serially correlated error term does not serve as a proxy for the lagged inflation term  $\pi_{t-1}$ . The estimates of  $\rho_2$  and  $\rho_3$  are statistically zero while the estimates of  $\rho_4$  are

statistically different from zero regardless of output gap measures. <sup>18</sup>

Table 4: Estimation Results - Sticky Inflation DSGE Model with ARMA(4,1) Cost Shocks: 1960:1-2008:4

gap measure	CBO	HP	CF
$c$	117.7 (75.9, 161.1)	140.1 (105.8, 170.6)	130.4 (95.0, 165.9)
$\theta$	0.68 (0.56, 0.80)	0.72 (0.64, 0.79)	0.73 (0.64, 0.81)
$\rho_1$	0.20 (0.04, 0.35)	0.02 (-0.11, 0.16)	0.05 (-0.10, 0.19)
$\rho_2$	0.06 (-0.06, 0.17)	-0.05 (-0.16, 0.04)	-0.05 (-0.15, 0.05)
$\rho_3$	0.08 (-0.03, 0.18)	0.01 (-0.07, 0.12)	0.03 (-0.05, 0.14)
$\rho_4$	0.22 (0.13, 0.30)	0.11 (0.04, 0.18)	0.15 (0.07, 0.23)
$\delta$	0.38 (0.20, 0.55)	0.30 (0.15, 0.44)	0.29 (0.13, 0.43)
likelihood	-906.1	-867.3	-824.8

## 5 Conclusion

One of the most popular ways to generate inflation persistence in the literature is to assume that a fraction of firms reset their prices by automatic indexation to past period's inflation rate. The indexation models have been criticized for the lack of microfoundations backing the introduction of the lagged inflation term in the Phillips curve. This paper proposes a model in which a lagged inflation term is endogenously generated from the optimizing behavior of forward-looking firms. Our results show that prices could be sticky in terms of the size and frequency of price adjustment. The estimated results on the frequency of price changes closely match extensive microdata evidence. The proposed sticky inflation model satisfactorily explains the presence small and large price change, the frequency of price changes, the impulse response functions of variables, and the observed dynamic behavior between output gap and inflation. Our model provides structural interpretations of properties inherent in the data. In particular, the model provides a theoretical foundation and interpretation for the resulting inertial inflation and a delayed, gradual impact of demand and monetary shocks on inflation. Such an effect is produced because even the chosen new price at discrete time intervals is only partially adjusted. These results indicate that the sticky inflation model with both staggered prices and costs of adjustment is in closer agreement with the data than that of the NKPC model.

<sup>18</sup>The importance of the role of  $\epsilon_{t-4}^{\pi}$  in accounting for inflation dynamics is likely to be associated with the absence of the lagged inflation term  $\pi_{t-4}$  in the Phillips curve. Roberts (2006) points out that the addition of a four-quarter moving-average of past inflation to the NKPC helps fit considerably better.

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