Dynamics of Sticky Information and Sticky Price Models in a New Keynesian DSGE Framework

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August 2007

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August, 2007

(First Draft, February, 2005)

Abstract

Recent literature on monetary policy analysis extensively uses the sticky price model of price adjustment in a New Keynesian Macroeconomic framework. This price setting model, however, has been criticized for producing implausible results regarding inflation and output dynamics. This paper examines and compares dynamic responses of the sticky price and sticky information models to a cost-push shock in a New Keynesian DSGE framework. It finds that the sticky information model produces more reasonable dynamics through lagged, gradual and hump-shaped responses to a shock as observed in data. However, these responses depend on the persistence of the shock.

JEL classification: E31; E32; E52

Keywords: Monetary policy; Sticky information; Sticky prices; Phillips curve

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*I thank David Papell, Bent Sørensen, Mark Bils and an anonymous referee for the valuable suggestions and comments. I would like also thank Ricardo Reis for helpful comments, feedback and pointing out some mistakes in earlier drafts of this paper. I also benefited from seminar participants at University of Houston, Texas Camp Econometrics X, and SEA Conference at Washington D.C. for useful comments on earlier drafts of this paper.

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1. Introduction

Much research has recently explored monetary policy analysis in which dynamic general equilibrium techniques of real business cycle analysis were adapted, and some nominal price rigidities were included to obtain a framework suitable for monetary policy analysis.[1] In such a framework, which is called the *New Keynesian*, agents are assumed to solve dynamic optimization problems in monopolistically competitive markets with some nominal price or wage stickiness. Many such recent studies led to the sticky price Phillips curve, which is mostly based on Calvo's (1983) model.[2]

In a typical New Keynesian macroeconomic model, the demand side is represented by an IS equation and the supply side by the sticky price Phillips curve. These behavioral equations are obtained explicitly from the optimization of households and firms. The framework is generally closed by assuming a monetary policy rule. This rule is usually in the form of an interest rate rule proposed by Taylor (1993), which is a feedback rule and determines the interest rates according to the deviations of output and inflation from their target levels. The sticky price Phillips curve in such a framework has been criticized for producing unrealistic output and inflation dynamics.

As an alternative to the sticky price Phillips curve, Mankiw and Reis (2002) proposed the "sticky information Phillips curve." The main premise of their model is that information about macroeconomic conditions spreads slowly throughout the population; although prices are set every period, information collecting and processing take time. In this model, a fraction of firms get complete information about the economy in each period randomly and independent of waiting time and set their prices according to this new information, while the remaining firms set their prices according to old information. Using a simple quantity equation instead of an IS curve, and an exogenous stochastic process for money supply instead of an interest rate rule, they showed the maximum impact of a monetary

[1] Some early examples of such studies include Benassy (1995), Cooley and Hansen (1995), King and Watson (1996), Rotemberg and Woodford (1995, 1997), Yun (1996), Goodfriend and King (1997), McCallum and Nelson (1999a, 1999b, 2000), Clarida, Gali and Gertler (1999), Woodford (1999).

[2] Rotemberg (1987) obtained the standard Calvo-type sticky price Phillips curve formulation by assuming quadratic costs of changing prices.

shock on inflation occurs after a substantial delay and the responses are hump-shaped in their model.

In this paper, dynamic responses of the sticky information Phillips curve and a standard sticky price Phillips curve to a unit cost-push shock[3] are investigated and compared in a New Keynesian dynamic stochastic general equilibrium (DSGE) model, which includes an IS equation and a Taylor-type policy rule for monetary authority. In recent literature there are a few studies which compare the sticky price and sticky information models. Such as Trabandt (2006) compares these two models under monetary and technology shocks and finds out that they both performs well in delivering the facts observed in data. Keen (2006) makes a similar study and obtains that two models behave similarly and inflation peaks immediately after a monetary shock when the nominal interest rate is used as the policy instrument. However, the sticky information model produces more plausible dynamics when the policy instrument is money growthin his study.

The first contribution of this paper to the literature is to integrate the sticky information Phillips curve into a DSGE model, where aggregate demand curve is represented by an IS equation and a Taylor-type interest-rate feedback policy rule is assumed for monetary authority rather than a simple quantity equation and exogenous money supply process as in Mankiw and Reis (2002). Second contribution is to investigate and compare the dynamic responses for a cost-push shock unlike the monetary or productivity shocks as in Mankiw and Reis (2002), Trabandt (2006) and Keen (2006). Therefore, this paper tries to find out whether the results of Mankiw and Reis are robust to different assumptions about aggregate demand, shocks and the nature of monetary policy.

In literature, there are many versions of the sticky price model that are obtained by modifying or extending the standard model.[4] In this study, use of the standard benchmark model is preferred, and it is compared with the sticky information model to be able to see the basic differences between these two modeling approaches.

[3]A cost-push shock represents everything other than the output gap that may affect the marginal cost, and causes the model to generate inflation variation independent of the demand shock. See Clarida, Gali and Gertler (1999, 2001, 2002), Ball, Mankiw and Reis (2004).

[4]See Woodford (2003) for some extensions of the standard model. Also Gali and Gertler (1999) proposed a "hybrid" Phillips curve by adding a lagged inflation term to the standard model.

The results show that impulse responses of the variables to a unit cost-push shock are hump-shaped and the maximum deviations from steady states occur at some quarters after the shock in the sticky information model as observed in data. However, those responses for the sticky price model are not hump-shaped and the maximum deviations occur immediately with the shock contrary to data. These differences in responses are mainly due to the differences in the structure of expectations in both models. In the sticky price model expectations are forward looking, that is current expectations of future economic conditions are important. Thus the maximum impact of the shock on variables occurs immediately with the shock when new expectations are formed due to the shock. Then these variables move towards their steady states because expectations include that monetary authority will response to this shock. However, in the sticky information model, past expectations of the current economic conditions matter as some firms use old information. Therefore, variables further deviate from their steady state after the shock and the maximum deviations occur at some quarters later because of those past expectations, which are formed before the shock and so are not affected by the shock. It is also observed that hump-shaped responses to the shock in the sticky information model depend on the persistence of the shock. If the shock is not persistent enough then the model produces less hump-shaped dynamic responses.

The simulations show that both models exhibit enough inflation persistence to a cost-push shock, however variables are more persistent in the sticky information model. In both models, the persistence and levels of the responses depend on the persistence of the shock term, and there is a positive correlation between them. The results also show that stabilization requires strong interest rate responses to the shock, especially strong response to the deviation of inflation from its target level, as in the Taylor principle. Strong inflation and output responses to the shock produce lower standard deviations of inflation and output, respectively. Also, dynamic responses are more sensitive to deviation of inflation from its target than to deviation of the output gap in both models. Therefore, choosing the policy parameter for the response to inflation deviations is the critical part in designing monetary policy with a Taylor-type rule. It is also observed that sticky information model produces more stabilization in the sense that standard deviations of the variables are less sensitive to the correlation coefficient of the shock when it is large and close to one, while sticky price model stabilizes more when the shock is not very persistent and the correlation coefficient is small and close to zero.

The volatility tradeoff of both models is also compared for different policy alternatives. Those tradeoffs are similar especially for policy responses to the deviations in the output gap. However, it could be concluded from this analysis that the sticky price model produces somewhat more stable inflation dynamics, while the sticky information model produces more stable output dynamics. It is also observed from the results that variables overshoot their long-run level in the sticky information model if the shock is not persistent enough, however there are no such overshoots in the sticky price model. Therefore, some of the initial price increase due to the shock is taken back when inflation overshoots and becomes negative, and "bygones be bygone" is not always valid in the sticky information model.

In the next section, the New Keynesian macroeconomic model and the sticky information model of price setting are explained. In Section 3 monetary policy framework is given and explained. In section 4 impulse responses are obtained for both models. Section 5 summarizes the conclusions obtained in this study.

2. Model and Price Settings

The model is a version of the standard New Keynesian dynamic general equilibrium model with price rigidities, which has been used extensively for theoretical analyses of monetary policy. In such a model there are several approaches to introduce the cost-push shock. In this study, households are assumed to be monopolistically competitive suppliers of their labor to obtain the cost-push shock term.[5]

The economy is closed and composed of a continuum of identical infinitely lived households indexed by $i \in [0, 1]$ and a continuum of firms indexed by $j \in [0, 1]$. Households

[5] This shock might also arise from the collusion among firms or from variable taxation as in Ball, Mankiw and Reis (2004).

supply labor, which is an imperfect substitute of other labors, purchase consumption goods and hold bonds. Firms hire labor and specialize in the production of a single good that is an imperfect substitute of other goods. Since each firm and household has some monopoly power, the economy is the one having the monopolistically competitive markets similar to those studied in Dixit and Stiglitz (1977) or Blanchard and Kiyotaki (1987).

Each firm sets the price of the good it produces either according to the sticky price or sticky information assumptions. Households and firms behave optimally and maximize their utility and profits, respectively. There is also a financial market in the economy in which households can trade in a range of securities that is large enough to completely cover all states of nature; that is, complete market is assumed and the households can insure themselves against idiosyncratic uncertainty.

2.1. Households

Households' preferences over consumption bundles are assumed identical, and they derive utility from composite consumption goods and leisure. The utility of household i in period t is given by

$$U_{it} = \frac{C_{it}^{1-\sigma}}{1-\sigma} - \frac{N_{it}^{1+\varphi}}{1+\varphi} \, , \tag{1}$$

where C_{it} is a Dixit-Stiglitz type CES aggregator of composite consumption of household i and is defined over the production C_{it}^{j} of firm j as

$$C_{it} = \left(\int_0^1 (C_{it}^{j})^{\frac{\varepsilon-1}{\varepsilon}} dj \right)^{\frac{\varepsilon}{\varepsilon-1}} . \tag{2}$$

N_{it} is household i's labor supply in period t. Parameter ε is the elasticity of substitution among the goods and is greater than one. Parameter φ is the marginal disutility of labor and is positive.[6] Parameter σ is the risk aversion factor and $1/\sigma$ represents the elasticity of intertemporal substitution in aggregate consumption evaluated at steady state.[7]

[6]It can be interpreted as the inverse of the Frisch elasticity of labor supply.
[7]Intertemporal elasticity of substitution is defined as : $1/\sigma \equiv -U_c/U_{cc}\bar{C}$.

Each household i seeks to maximize the lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U_{it} \ , \tag{3}$$

where $\beta < 1$ is the discount factor. The maximization will be subject to the intertemporal budget constraint

$$\int_0^1 C_{it}^j P_{jt} \, dj + E_t(Q_{t,t+1} D_{t+1}) \leq D_t + \int_0^1 W_{it} N_{it}^j \, dj \ , \tag{4}$$

where P_{jt} is the price of the goods produced by firm j, D_{t+1} denotes the nominal value of the portfolio of financial assets in period $t+1$ that the household holds at the end of period t. $Q_{t,t+1}$ is the stochastic discount factor for nominal payoffs of assets. No arbitrage opportunities requires that assets prices should be determined by such discount factors, and markets are complete so that households can obtain any random payoff D_{t+1} at a price of $E_t(Q_{t,t+1} D_{t+1})$. W_{it} is the nominal wage of the labor supplied by household i.

Optimization problem of the household can be divided into two steps. First, household i allocates its consumption bundle to minimize the total expenditure required to achieve any desired level of composite consumption index C_{it}. Then, in the second step, it will choose optimum consumption level C_{it} and optimum labor supply N_{it} given the minimum cost level from the first step. First step yields

$$C_{it}^j = \left(\frac{P_{jt}}{P_t} \right)^{-\varepsilon} C_{it} \ , \tag{5}$$

so ε can also be interpreted as the price elasticity of demand for good j. P_t is the aggregate price index and defined as

$$P_t = \left(\int_0^1 P_{jt}^{1-\varepsilon} dj \right)^{\frac{1}{1-\varepsilon}} . \tag{6}$$

Since households are monopolistically competitive suppliers of their labor, they face the demand function for their services by firm j as

$$N_{it}^j = \left(\frac{W_{it}}{W_t} \right)^{-\eta_t} N_{it} \ , \tag{7}$$

where η_t is the elasticity of labor demand which is the same across households, and W_t is the aggregate wage index and defined as

$$W_t = \left(\int_0^1 W_{it}^{1-\eta_t} di \right)^{\frac{1}{1-\eta_t}} . \tag{8}$$

The budget constraint in (4) can be rewritten by using the above results as

$$P_t C_{it} + E_t(Q_{t,t+1} D_{t+1}) = D_t + W_t N_{it} \,. \tag{9}$$

Then the first order conditions from maximizing (3) subject to the budget constraint (9) are obtained as

$$C_{it}^{\sigma} N_{it}^{\varphi} = \frac{\varepsilon}{\varepsilon - 1} \frac{\eta_t - 1}{\eta_t} \frac{W_t}{P_t} \,, \tag{10}$$

$$\frac{W_t}{P_t} = \frac{\mu_t^w}{\mu} C_{it}^{\sigma} N_{it}^{\varphi} \,, \tag{11}$$

$$\beta I_t E_t \left\{ \left(\frac{C_{it+1}}{C_{it}} \right)^{-\sigma} \left(\frac{P_t}{P_{t+1}} \right) \right\} = 1 \,, \tag{12}$$

where $\mu_t^w = \frac{\eta_t}{\eta_t - 1}$ is the optimal wage markup, $\mu = \frac{\varepsilon}{\varepsilon - 1}$ is the constant price markup, and $E_t(Q_{t,t+1}) = I_t^{-1}$ is the price of a riskless one-period asset. Therefore,

$$c_{it} = E_t c_{it+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1} + \ln \beta) \tag{13}$$

can be obtained, where small characters represent the logarithm of those variables, and $\pi_t = p_t - p_{t-1}$ is the inflation rate, and i_t is the nominal interest rate at period t.

Wages are perfectly flexible here, so there is no endogenous variation in the wage markup resulting from any wage stickiness. However, as in Clarida et al. (2002), shifts in the η_t result in exogenous variation in the wage markup, and those shifts may be interpreted as exogenous variation in labor market power of households.

2.2. Firms

Each firm j produces its specialized product with a linear technology according to the production function

$$Y_{jt} = A_t N_{jt} \,. \tag{14}$$

That is, output is only the function of labor input N_{jt} and aggregate productivity disturbance A_t. Capital is just ignored in the production function for simplicity. Labor input for firm j is given by a CES aggregator of individual household labor N_{it}^j as

$$N_{jt} = \left(\int_0^1 (N_{it}^j)^{\frac{\eta_t - 1}{\eta_t}} di \right)^{\frac{\eta_t}{\eta_t - 1}} \,. \tag{15}$$

Firms hire labor, and produce and sell their differentiated products in monopolistically competitive market. They minimize their cost of production, and their minimization problem yields

$$\gamma_t = \frac{2\mu_t^w - 1}{\mu_t^w} \frac{W_t/P_t}{A_t} \ , \tag{16}$$

where γ_t is the firm's real marginal cost. Since technology is constant returns to scale and shocks are the same across the firms, the real marginal cost γ_t is the same across all firms.

In a monopolistically competitive model, it is assumed that each firm knows that its sale depends on the price of its product. When all purchases are made for private consumption, then the aggregate demand Y_t corresponds to the households total consumption index. So, the demand function can be written from equation (5) as

$$\int_0^1 C_{it}^j \, di = \left(\frac{P_{jt}}{P_t}\right)^{-\varepsilon} \int_0^1 C_{it} \, di, \tag{17}$$

$$Y_{jt} = \left(\frac{P_{jt}}{P_t}\right)^{-\varepsilon} Y_t, \tag{18}$$

and in logs

$$y_{jt} = y_t - \varepsilon(p_{jt} - p_t) \ , \tag{19}$$

where y_{jt} is the output produced by firm j, p_{jt} is the price charged for that product by firm j, y_t is the aggregate output, and p_t is the price index for aggregate consumption.

Firms also decide what price P_{jt}^* to charge to maximize their profit given the demand function in equation (19). So, the firm j's decision problem gives

$$\frac{P_{jt}^*}{P_t} = \frac{\varepsilon}{\varepsilon - 1} \frac{W_t/P_t}{A_t} = \frac{\mu \mu_t^w}{2\mu_t^w - 1} \gamma_t \ . \tag{20}$$

This is the standard results in a monopolistic competitive market when all firms are able to adjust their price in every period; that is, each firm set its optimal price P_{jt}^* equal to a markup over its nominal marginal cost, $P_t\gamma_t$. By using equation (11), the above expression can be rewritten as

$$\frac{P_{jt}^*}{P_t} = \frac{\varepsilon}{\varepsilon - 1} \frac{\mu_t^w}{\mu} \frac{C_{it}^\sigma N_{it}^\varphi}{A_t} = \mu_t^w \frac{C_{it}^\sigma N_{it}^\varphi}{A_t} \ . \tag{21}$$

2.3. Equilibrium

Since households are identical and financial markets are complete, households will have the same initial wealth. As in Woodford (2002), this implies the same consumption decisions and a common level of consumption denoted by C_t, although the labor supply and output may change. Therefore, the market clearing conditions require consumption should be equal to output, so $C_{it} = C_t = Y_t$.

Since wages are flexible, each household will charge the same wage and provide the same amount of labor. So, $W_{it} = W_t$, and this implies $N_{it}^j = N_{it}$ from equation (7). Therefore, the labor market clearing condition can be written through equation (15) as $N_{jt} = N_{it}$. Then, by using the production function in (14) and the demand function in (19), equation (21) can be rewritten as

$$\frac{P_{jt}^*}{P_t} = \mu_t^w \frac{1}{A_t^{1+\varphi}} \left[\left(\frac{P_{jt}^*}{P_t} \right)^{\frac{-\varepsilon\varphi}{\sigma+\varphi}} Y_t \right]^{\sigma+\varphi} , \tag{22}$$

$$p_{jt}^* = p_t + \frac{\sigma+\varphi}{1+\varepsilon\varphi} y_t - \frac{1+\varphi}{1+\varepsilon\varphi} a_t + \frac{\log \mu_t^w}{1+\varepsilon\varphi} . \tag{23}$$

When all firms can set their prices freely in each period, that is when prices are flexible, all firms set the same price $p_{jt}^* = p_t$. The natural level of output y_t^N is defined as the level where prices are flexible and the wage markup is fixed at its steady state value μ^w. This setup means there are no wage markup shocks, and variations in the natural level of output do not reflect the variations in the wage markup. Therefore, under flexible price equilibrium, equation (23) yields

$$y_t^N = \frac{1+\varphi}{\sigma+\varphi} a_t - \frac{\log \mu^w}{\sigma+\varphi} . \tag{24}$$

If this is used in (23), one can obtain

$$p_{jt}^* = p_t + \alpha(y_t - y_t^N) + u_t , \tag{25}$$

where α and the cost-push shock term u_t are defined as

$$\alpha = \frac{\sigma+\varphi}{1+\varepsilon\varphi} \quad , \quad u_t = \frac{\log(\mu_t^w/\mu^w)}{1+\varepsilon\varphi} .$$

Therefore, in the framework of this study the cost-push shock term can be interpreted to represent the bargaining power of households in the labor market.

When equation (13) is aggregated over all households, it can be written in terms of aggregate output index as

$$y_t = E_t y_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1} + \ln \beta) \; . \tag{26}$$

With the assumption of an exogenous AR(1) technology shock process $a_t = \rho_a a_{t-1} + \xi_t$, this equation can be written in terms of the output gap $x_t = y_t - y_t^N$ as

$$x_t = E_t x_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1}) + \nu_t \; , \tag{27}$$

where $\nu_t = -\frac{\log \beta}{\sigma} - \frac{(1-\rho_a)(1+\varphi)}{\sigma+\varphi} a_t$. This is the IS equation used in the New Keynesian framework.

2.4. Price Settings

Price adjustment is the dynamic connection between monetary and real variables. The specific manner of how prices adjust affects demand and production. Therefore the price adjustment model is very important for the implication of models for monetary policies.

2.4.1. The Sticky Price Model

The most common type of price adjustment model recently used in literature is the sticky price model, which is usually based on the Calvo model. In this model firms set nominal prices on a staggered basis. Each firm adjusts its price with some probability in each period, independent of the waiting time. Thus, during each period a number of randomly selected fraction $1-\theta$ of firms change their prices while the remaining fraction θ of firms keep their prices unchanged. Firms that do not adjust their prices will adjust their output according to demand function of the market. The standard sticky price Phillips curve resulting from this model can be obtained in our framework as

$$\pi_t = \kappa x_t + \beta E_t \pi_{t+1} + \phi(1-\beta\theta) u_t \; , \tag{28}$$

where x_t is the output gap, $\phi = (1-\theta)/\theta$, and κ is a constant given by model's parameters as $\kappa = \phi\alpha(1-\beta\theta)$.

The sticky price Phillips curve relates current inflation to the current output gap and expected next-period inflation rate. Therefore, the price setting is forward-looking in this model. By iterating equation (28), it can be seen that adjusting firms set their prices as a markup over a weighted average of the expected future output gap because the price they set will remain unchanged for a random number of periods.[8]

Although the sticky price Phillips curve has been used as the "workhorse" in literature and has an appealing theoretical structure, it has been criticized for producing implausible results regarding inflation and output dynamics. Criticism includes that the sticky price model does not exhibit the inflation persistence and delayed and gradual effects of shocks observed in data.[9] It is also unable to account for the correlation between inflation and the output gap. The sticky price model implies that inflation should lead the output gap over the cycle, although VAR studies have shown that the main effect of a shock on output precedes the effect on inflation. It also has difficulty in explaining the correlation between the change in inflation and the output gap.[10] This model violates the natural rate hypothesis and implies that an increasing inflation rate will tend to keep output permanently low. Ball (1994) showed that credible disinflations cause booms rather than recession with this model.[11] Because of such problems with the sticky price model, there have been some extensions and alternatives to this model.[12]

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[8]In our set up the output gap represents the real marginal cost. In general, firms set their optimal prices as a markup over the expected future real marginal cost.

[9]Fuhrer and Moore (1995) argue incapability of producing inflation persistence in the sticky price model. However, if a persistence is allowed in the level of nominal marginal cost, then sticky price model could produce very persistent inflation. Also, as Taylor (1999) argues inflation persistence could be due to serial correlation of money growth process. Therefore, as Mankiw and Reis (2002) discusses, the key problem with the sticky price model is not the persistence of the dynamic responses but the delayed and gradual responses to shocks.

[10]Acceleration phenomenon in Mankiw and Reis (2002).

[11]See, among others, Ball (1994), Fuhrer and Moore (1995), Estrella and Fuhrer (1998), Lown and Rich (1997), Roberts (1997, 1998) and Gali and Gertler (1999) for empirical difficulties with the sticky price Phillips curve.

[12]See Woodford (2003).

2.4.2. The Sticky Information Model

As an alternative to the sticky price model, Mankiw and Reis (2002) proposed the sticky information model, which leads to the sticky information Phillips curve. They argue that dynamics of their model are similar to backward-looking expectations models, and the expectation structure is close to the Fisher's contracting model. This model assumes information of macroeconomic conditions spreads slowly throughout the population. In this model, prices are set every period, but information collecting and processing, that is optimal price computing, occur slowly over time. Each period, a randomly selected fraction $1-\theta$ of firms receive complete information about the state of the economy and adjust their prices according to this new information, while the remaining fraction θ of firms set their prices according to old information. When a firm j sets its price in period t, it will set it to its optimal expected price according to the last information it has at period $t-k$ as

$$p_{jt}^{k} = E_{t-k} p_{jt}^{*} \; . \tag{29}$$

A first order approximation of the aggregate price index equation (6) can be given by

$$p_t = \int_0^1 p_{jt}\, dj \; .$$

Since the new information arrives at a rate of $1-\theta$, the share of the firms that last adjusted their plan k periods ago will be $(1-\theta)\theta^k$. So the price index can be written as

$$p_t = (1-\theta) \sum_{k=0}^{\infty} \theta^k E_{t-k} p_{jt}^{*} \; . \tag{30}$$

By using the p_{jt}^{*} from equation (25), the price index becomes

$$p_t = (1-\theta) \sum_{k=0}^{\infty} \theta^k E_{t-k} [p_t + \alpha(y_t - y_t^N) + u_t] \; . \tag{31}$$

Then, the sticky information Phillips curve can be obtained from this equation as

$$\pi_t = \frac{\alpha(1-\theta)}{\theta}\, x_t + \frac{(1-\theta)}{\theta}\, u_t + (1-\theta) \sum_{k=0}^{\infty} \theta^k E_{t-1-k} (\pi_t + \alpha \Delta x_t + \Delta u_t),$$

$$\pi_t = \phi\alpha\, x_t + \phi\, u_t + (1-\theta) \sum_{k=0}^{\infty} \theta^k E_{t-1-k} (\pi_t + \alpha \Delta x_t + \Delta u_t), \tag{32}$$

where ϕ and α are the same as given above. In the sticky information model, expectations are the past expectations of current economic conditions. This model also satisfies the natural rate hypothesis. Because, without any surprises, the model implies that $p_t = E_{t-j}p_t$, and this implies $x_t = 0$.

Mankiw and Reis examined the dynamic properties of the sticky information model. They used a simple aggregate demand equation and assumed a stochastic AR(1) process for the money supply, and then obtained the dynamic responses to a monetary policy shock and compared their model with the sticky price model and a backward-looking model. Due to their results, the sticky information model can explain a long lag between monetary policy actions and inflation, while the sticky price model cannot. They also showed that disinflations are always contractionary, and strong economic activity is positively correlated with increasing inflation in the sticky information model.

3. Monetary Policy Framework and Solving the Models

3.1. Monetary Policy Framework

In this study, the sticky information model is compared with the sticky price model in a New Keynesian framework by assuming a Taylor rule for monetary policy and a cost-push shock to the economy. In the above analysis, the structural equations of price adjustment and IS are obtained. If a central bank can commit to a simple instrument rule like a Taylor-type interest rate rule to stabilize inflation and output fluctuations, then this rule is combined with the structural equations to close the model and to obtain a framework for the analysis of monetary policy. Therefore, the dynamic responses of the sticky information model would be obtained from these three equations, which are given below

$$x_t = E_t x_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1}) + \nu_t, \tag{33}$$

$$\pi_t = \phi\alpha\, x_t + \phi\, u_t + (1-\theta)\sum_{k=0}^{\infty}\theta^k E_{t-1-k}(\pi_t + \alpha\Delta x_t + \Delta u_t), \tag{34}$$

$$i_t = \delta_\pi \pi_t + \delta_x x_t + e_t. \tag{35}$$

The policy parameters δ_π and δ_x that are given in the Taylor rule (35) are the interest rate responses of the central bank to the deviations of inflation and the output gap from their target levels, respectively. The disturbances in the model are represented by the terms ν_t, u_t and e_t.

The framework needed for the analysis of the sticky price model is the same given above except the price adjustment equation. So this framework is just obtained by replacing equation (34) with the sticky price Phillips curve given in equation (28).

In order to put those three equations into a matrix system, first, equation (34) is written for period $t+1$, and then the expectations are taken at period t to obtain the following expression

$$\begin{aligned}\theta E_t\pi_{t+1} - (\alpha\phi + \alpha(1-\theta))E_t x_{t+1} &= -\alpha(1-\theta)x_t + \phi\, E_t u_{t+1} + (1-\theta)E_t\Delta u_{t+1} \\ &\quad + (1-\theta)\sum_{k=1}^{\infty}\theta^k E_{t-k}(\pi_{t+1} + \alpha\Delta x_{t+1} + \Delta u_{t+1})\,. \end{aligned} \tag{36}$$

If i_t is eliminated by using equation (35), the IS equation can be rewritten as

$$E_t\pi_{t+1} + \sigma E_t x_{t+1} = \delta_\pi \pi_t + (\sigma + \delta_x)x_t + e_t - \sigma\nu_t. \tag{37}$$

Then the dynamic system from equations (36) and (37) is given by

$$\begin{bmatrix}\theta & -\alpha(\phi + (1-\theta)) \\ 1 & \sigma\end{bmatrix}\begin{bmatrix}E_t\pi_{t+1} \\ E_t x_{t+1}\end{bmatrix} = \begin{bmatrix}0 & -\alpha(1-\theta) \\ \delta_\pi & \sigma + \delta_x\end{bmatrix}\begin{bmatrix}\pi_t \\ x_t\end{bmatrix} +$$
$$\begin{bmatrix}\phi\, E_t u_{t+1} + (1-\theta)E_t\Delta u_{t+1} + (1-\theta)\sum_{k=1}^{\infty}\theta^k E_{t-k}(\pi_{t+1} + \alpha\Delta x_{t+1} + \Delta u_{t+1}) \\ e_t - \sigma\nu_t\end{bmatrix}, \tag{38}$$

and it can be written as

$$\begin{bmatrix}E_t\pi_{t+1} \\ E_t x_{t+1}\end{bmatrix} = M\begin{bmatrix}\pi_t \\ x_t\end{bmatrix} + N_t\,, \tag{39}$$

where

$$M = \begin{bmatrix}\dfrac{\delta_\pi(\alpha\phi + \alpha(1-\theta))}{s} & \dfrac{(\alpha\phi + \alpha(1-\theta))(\sigma + \delta_x) - \sigma\alpha(1-\theta)}{s} \\ \dfrac{\delta_\pi\theta}{s} & \dfrac{\theta(\sigma + \delta_x) - \alpha(1-\theta)}{s}\end{bmatrix},$$

$$N_t = \begin{bmatrix}\sigma/s & (\alpha\phi + \alpha(1-\theta))/s \\ -1/s & \theta/s\end{bmatrix}$$

$$\begin{bmatrix} \phi\, E_t u_{t+1} + (1-\theta) E_t \Delta u_{t+1} + (1-\theta) \sum_{k=1}^{\infty} \theta^k E_{t-k}(\pi_{t+1} + \alpha \Delta x_{t+1} + \Delta u_{t+1}) \\ e_t - \sigma \nu_t \end{bmatrix},$$

and $\quad s = \sigma\theta + \alpha\phi + \alpha(1-\theta)$.

Matrix M is the characteristic matrix of the system given in (39), and matrix N_t is composed of disturbance terms and predetermined variables, which are know at time t. This system has a unique and bounded solution for inflation and the output gap *if and only if both eigenvalues of matrix M have modulus greater than one*; and if this is the case the solution can be obtained by solving forward.[13]

For the sticky price model, the corresponding matrix M satisfies this determinacy requirement if the interest rate response to the deviations either in inflation or in the output gap is strong enough (such as satisfying the Taylor principle: $\delta_\pi > 1$). However, matrix M for the sticky information model given in (39) does not satisfy this determinacy requirement. It can be easily demonstrated that matrix M for the sticky information model has two positive roots, with one root is greater than one and the other is less than one.[14] Thus, such a dynamic system has an infinite number of bounded rational expectation solutions as explained in Svensson and Woodford (2003). Therefore, some additional condition is needed to solve this indeterminacy problem and get a unique solution.

One such condition can be obtained from the framework above. The matrix system in (39) is obtained by expressing the sticky information Phillips curve given in (34) for period $t+1$, and then taking its period t expectation. However, equation (34) has to be satisfied by any solution to (39), so this equation can be used to obtain a unique, bounded rational expectation solution.

3.2. Solution for the Cost-push Shock

The solution technique that will be used to solve the above system is to write all variables in an infinite MA representation and then find the coefficients in these repre-

[13]See Svensson and Woodford (2003) for details of indeterminacy problem.

[14]This is the case if $\delta_\pi \geq 1$. If $\delta_\pi < 1$, then both eigenvalues of matrix M have modulus less than one, so there will be no solution for this case.

sentations when a cost-push shock process is assumed.[15] A stationary cost-push shock process $u_t = \rho u_{t-1} + \varepsilon_t$ is assumed, where ε_t is a white noise process with mean zero. Inflation and the output gap are represented as infinite moving average processes of the innovation terms ε_t as

$$\pi_t = \sum_{i=0}^{\infty} \gamma_i \varepsilon_{t-i}, \qquad x_t = \sum_{i=0}^{\infty} \beta_i \varepsilon_{t-i}.$$

The solution requires determining the γ_i and β_i coefficients of these MA processes.

Dynamic responses for a cost-push shock are obtained by solving the version of the system (39) which only contains the cost-push shock term. Since cost-push shock is unexpected, the past expectations about the current and future shock terms are zero.[16] Therefore, for a unit cost-push shock when other disturbances are assumed to be absent, the matrix N_t of the system reduces to

$$N_t = \begin{bmatrix} \sigma/s & (\alpha\phi + \alpha(1-\theta))/s \\ -1/s & \theta/s \end{bmatrix} \begin{bmatrix} [\phi\rho - (1-\theta)(1-\rho)]u_t + (1-\theta)\sum_{k=1}^{\infty} \theta^k E_{t-k}(\pi_{t+1} + \alpha\Delta x_{t+1}) \\ 0 \end{bmatrix} \tag{40}$$

The resultant system can be solved, and one can obtain a bounded, unique rational expectation solution for inflation and the output gap. The technical details of this solution are given in appendix.

4. Dynamic Responses for the Cost-push Shock

4.1. The Calibration

To obtain impulse responses and some quantitative results of models, the model's parameters need to be calibrated. Three structural parameters of the model are θ, σ and

[15] In this study, dynamic implications of the sticky information model is analyzed and compared with the sticky price model by only assuming a cost-push shock to economy. However, as can been seen from the above framework, there may be two other disturbances to economy, namely demand shock ν_t and policy shock e_t. The analyses of the sticky information model under these shock processes are investigated in Arslan (2005).

[16] In the period of $t-1$, the economy is in steady state and no shock is expected. However, expectations change when an unexpected shock occurs at time t, and it is assumed that this unexpected cost-push shock follows an AR(1) process starting from time t.

φ. The parameter θ measures the degree of nominal rigidity or price stickiness in the economy, and it is assumed to be 0.75 as in Mankiw and Reis (2002). So, on average, each firms gets new information or opportunity to set its price in a year, which is in the accepted range for this duration.[17] In the baseline estimation, the other parameter values are calibrated as: risk aversion factor, $\sigma = 6$, which implies a small intertemporal elasticity of substitution (IES) of $1/\sigma = 0.167$; marginal disutility of labor, $\varphi = 0.5$[18], and elasticity of substitution among goods, $\varepsilon = 6$.

However, there is no consensus on the values of these parameters, especially on the intertemporal elasticity of substitution, so it is possible to see very different values assigned to them in literature. Many studies in literature estimate the intertemporal elasticity of substitution, but the estimates are widely different across these studies and are not robust to model specifications and time periods.[19] Therefore, robustness of the results in the baseline calibration need to be checked, and it is performed with different set of parameter values in the next section.

4.2. The Impulse Responses

Impulse responses of the sticky information and sticky price models to a unit cost-push shock are given in Figures 1 and 2, respectively. Both figures show the output gap, inflation, nominal and real interest rate paths for the correlation coefficient of the shock $\rho = 0.8$, and for different policy alternatives, which are represented by different values of

[17] Gali and Gertler (1999) estimated this duration as five to six quarters, while Sbordone (2002) estimated as nine to 14 months, and survey evidence shows this duration is somewhat less than the above figures and around three to four quarters. For some survey evidence on the degree of the price stickiness, see Blinder et al. (1998), Bils and Klenow (2002).

[18] This value of φ is very close to the one obtained in Rotemberg and Woodford (1997), which is 0.47.

[19] For example, among others, Hall (1988) reported estimates of IES ranging from -0.03 to 0.98, while the estimates obtained by Hansen and Singleton (1982, 1983) lie between 0.5 and 2, and estimates of Hansen and Singleton (1996) range from 1.73 to 11.61. Also, Beaudry and Wincoop (1996) find that IES is significantly different from zero and probably close to one in contrast to the result of Hall (1988) and Campbell and Mankiw (1989) by using US state-level data. Rotemberg and Woodford (1997) estimate IES as 6.25, and admit that this value is much greater than a typical value. They argue that IES represents the elasticity of expected output growth with respect to the expected real return in their study, a lower σ (so a higher IES) is possible because of more interest sensitivity of consumption of both consumer durables and investment goods. On the other hand, RBC literature generally assumes that $\sigma = 1$. Such as Cooley and Prescott (1995), the calibration of Chari et al. (2000) implies that $\sigma = 1$ and $\varphi = 1.25$.

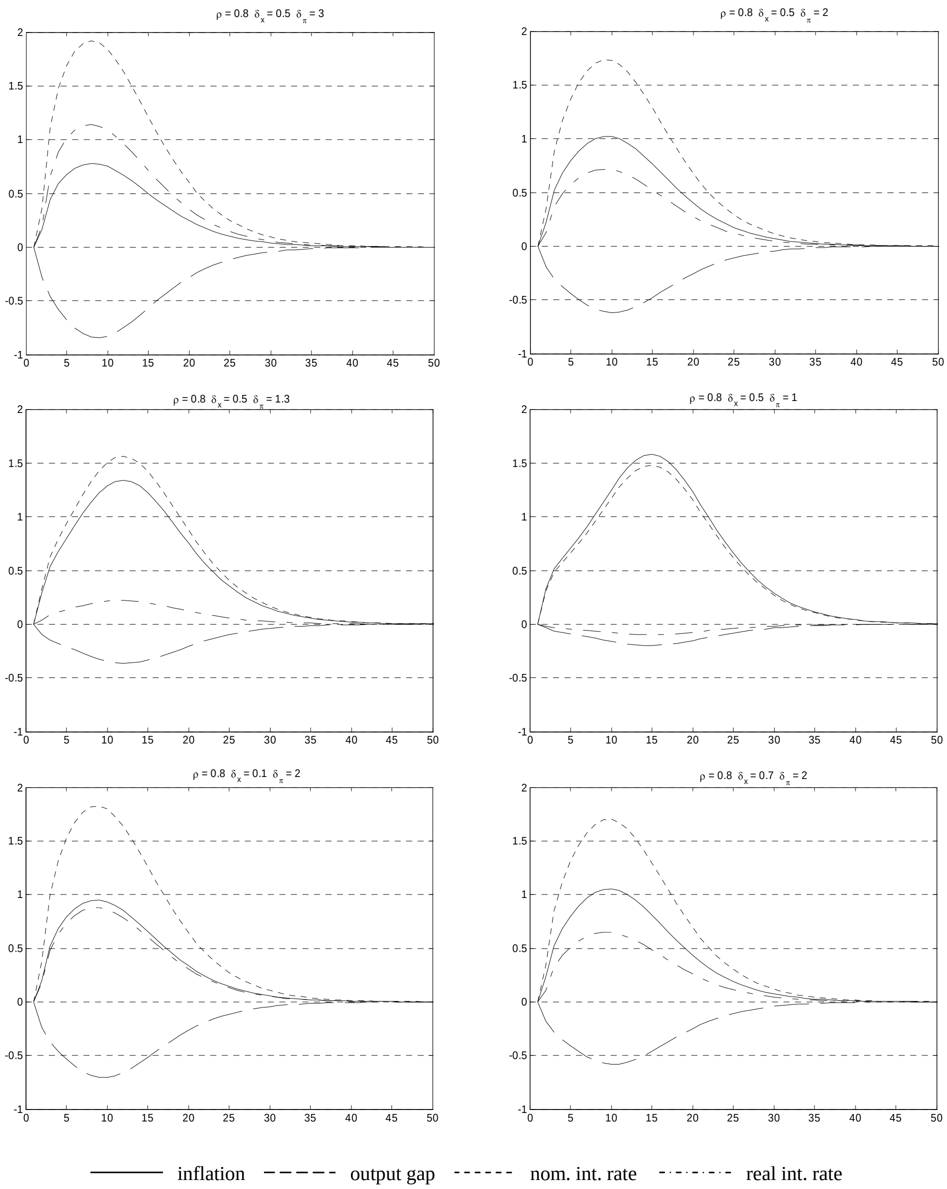

Fig. 1. Impulse responses of the sticky information model to a unit cost push shock. Policy rules are described by $i_t = \delta_\pi \pi_t + \delta_x x_t$. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

δ_π and δ_x in the Taylor rule.

In both models, a positive cost-push shock increases inflation through the price adjustment equations. The central bank responds to this inflation increase by increasing the nominal rates. If this response strong enough, the real rate increases; so the economy contracts and output decreases through the IS equation. Inflation reacts to this output decrease through expectations and starts to decrease, and this process continues until the

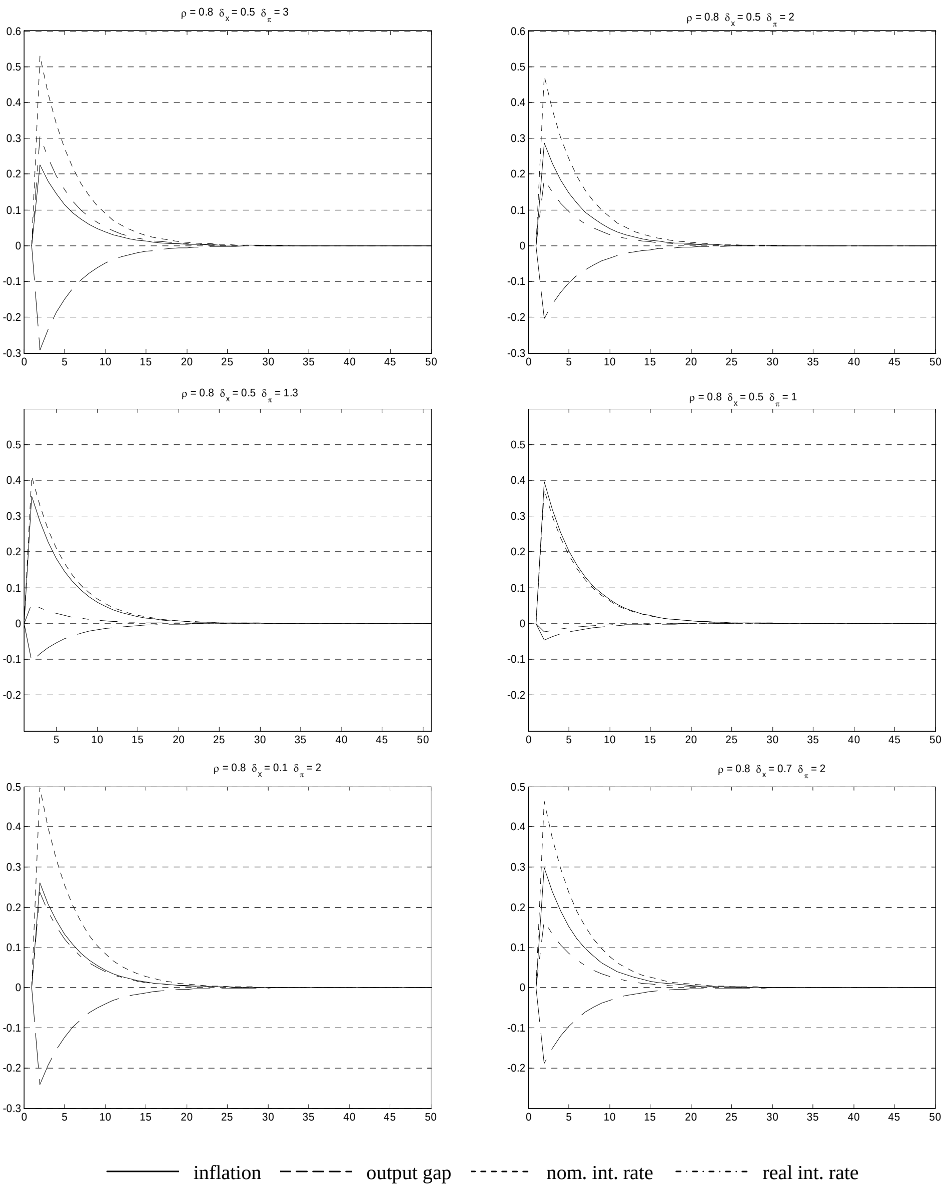

Fig. 2. Impulse responses of the sticky price model to a unit cost push shock. Policy rules are described by $i_t = \delta_\pi \pi_t + \delta_x x_t$. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

steady state values are reached. If the central bank's response to the shock is not strong enough, the real rate might be very small positive or even negative and so the economy contracts less but the inflation becomes higher as shown in these figures. Such as simulations show that when δ_π decreases from 3 to 1, inflation level due to the shock almost doubles in both models. The last rows of these figures show that dynamic responses of both models are not very sensitive to the policy parameter δ_x as much as δ_π; such as when

δ_x increases from 0.1 to 0.7, the dynamic responses of the models change little, and output and inflation increase only by a very small amount.

These figures clearly exhibit that impulse responses of both models have different shapes. The impulse responses of the variables to a unit cost-push shock are hump-shaped and the maximum deviations from steady states occur at some quarters after the shock in the sticky information model as observed in data. However, those responses for the sticky price model are not hump-shaped and the maximum deviations occur in the same period with the shock contrary to data.

These differences in responses result from the differences in the structure of expectations in both models. When a positive cost-push shock occurs and the central bank responds to it, expectations adjust and public expects inflation to decrease and output to increase after the shock. In the sticky price model expectations are forward looking, and so only the future expectations matter. When price setting firms use the lower expectations for future inflation, the inflation rate starts to decrease immediately after the shock. Therefore, maximum impacts of the shock on variables occur in the same period with the shock and they do not further increase and then gradually move towards their steady states. However, in the sticky information model, past expectations of current economic conditions are important. Some firms use old information, so the expectations in their price setting do not include those expectations about decreasing in future inflation. Therefore, variables further deviate from their steady state after the shock and the maximum deviations occur at some quarters later because of those past expectations, which are formed before the shock and so are not affected by the shock.

It can also be seen from Figures 1 and 2 that the variables are more persistent to a cost-push shock in the sticky information model than in the sticky price model. Since the sticky price model is sometimes criticized for not having enough inflation persistence observed in data, this feature of the sticky information model can be considered as an improvement over the sticky price model.

The standard deviations of the output gap, inflation, nominal and real interest rates for different policy alternatives and correlation coefficients of the cost-push shock are tab-

Table 1
Variations of variables to a cost-push shock for different policy rules

Policy Rules for $\rho = 0.8$	Sticky Information Model				Sticky Price Model			
	$sd(\pi)$	$sd(x)$	$sd(i)$	$sd(r)$	$sd(\pi)$	$sd(x)$	$sd(i)$	$sd(r)$
$\delta_x = 0.5,\ \delta_\pi = 3.0$	0.279	0.301	0.688	0.409	0.048	0.062	0.113	0.065
$\delta_x = 0.5,\ \delta_\pi = 2.0$	0.371	0.223	0.631	0.260	0.061	0.043	0.101	0.040
$\delta_x = 0.5,\ \delta_\pi = 1.7$	0.412	0.189	0.606	0.194	0.067	0.035	0.096	0.029
$\delta_x = 0.5,\ \delta_\pi = 1.5$	0.445	0.162	0.587	0.142	0.071	0.029	0.092	0.021
$\delta_x = 0.5,\ \delta_\pi = 1.3$	0.485	0.131	0.566	0.080	0.076	0.022	0.088	0.012
$\delta_x = 0.5,\ \delta_\pi = 1.0$	0.562	0.071	0.526	0.035	0.085	0.010	0.080	0.005
$\delta_x = 0.7,\ \delta_\pi = 2.0$	0.383	0.210	0.619	0.236	0.064	0.040	0.099	0.036
$\delta_x = 0.3,\ \delta_\pi = 2.0$	0.358	0.237	0.644	0.287	0.059	0.047	0.104	0.045
$\delta_x = 0.1,\ \delta_\pi = 2.0$	0.343	0.254	0.661	0.318	0.056	0.052	0.106	0.051

Notes: Policy rules are described by $i_t = \delta_\pi \pi_t + \delta_x x_t$. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

Table 2
Variations of variables to a cost-push shock with different autoregressive coefficients for the policy rule: $\delta_x = 0.5,\ \delta_\pi = 2$

	Sticky Information Model				Sticky Price Model			
ρ	$sd(\pi)$	$sd(x)$	$sd(i)$	$sd(r)$	$sd(\pi)$	$sd(x)$	$sd(i)$	$sd(r)$
0.9	0.498	0.329	0.832	0.334	0.092	0.092	0.139	0.046
0.7	0.402	0.222	0.693	0.291	0.042	0.024	0.073	0.030
0.5	0.125	0.053	0.223	0.098	0.024	0.010	0.043	0.019
0.3	0.027	0.011	0.049	0.022	0.017	0.006	0.030	0.014
0.1	0.010	0.004	0.018	0.008	0.013	0.004	0.023	0.011
0.0	0.005	0.002	0.009	0.004	0.011	0.003	0.021	0.010

Notes: Policy rule is described by $i_t = \delta_\pi \pi_t + \delta_x x_t$. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

ulated in Table 1 and 2, respectively. In these tables, different policy alternatives are represented by different values of δ_π and δ_x, and different correlation coefficients are represented by different values of ρ. Table 1 shows that stabilization requires strong interest rate responses to the shock. Strong inflation and output responses (large values of δ_π and δ_x) to the shock result in lower standard deviations of inflation and the output gap, respectively. This result confirms the Taylor principle in a sense that stabilization requires strong responses to the shock. The lower panel in Table 1 shows that dynamic responses and volatility of the variables are more sensitive to δ_π than δ_x in both models. Therefore, choosing the policy parameter δ_π is more important than choosing δ_x in designing monetary policy with a Taylor-type interest rate rule when there is a cost-push shock.

Table 2 gives the standard deviations of the variables for different correlation coefficients of the cost-push shock. It can be seen from this table for a given δ_x and δ_π that the sticky information model produces more stabilization in a sense that standard deviations of the variables are less sensitive to the changes in correlation coefficient of the shock when it is large and close to one, while the sticky price model stabilizes more when correlation coefficient is smaller and close to zero.[20] Therefore, the sticky information model produces more stable economy for persistent shocks, while the sticky price model for non-persistent shocks.

As pointed out in Clarida et al. (1999), there is a short-run tradeoff between output and inflation in the presence of the cost-push shock, and this tradeoff is obvious in the dynamic responses shown in Figures 1 and 2. That is, if policy rule to the shock aims lower inflation then output decreases more, or vice versa. There is also a volatility tradeoff between inflation and the output gap as can be seen from Table 1. This volatility tradeoff implications of both models can also be demonstrated and compared by drawing the efficient policy frontier, which shows the standard deviations of the output gap and inflation under some policy objectives.

Figure 3 shows the efficient policy frontiers for both models when either δ_π is fixed and δ_x is changed, or vice versa. Those tradeoffs are similar especially for policy responses to the deviations in the output gap, that is when δ_x changes and δ_π remains fixed. However, the right panel of the figure implies that the sticky price model produces somewhat more stable inflation dynamics since it has steeper curve, while the sticky information model produces more stable output dynamics since it has flatter curve.

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[20] Although the results are not shown here, similar findings were obtained for some other different policy alternatives.

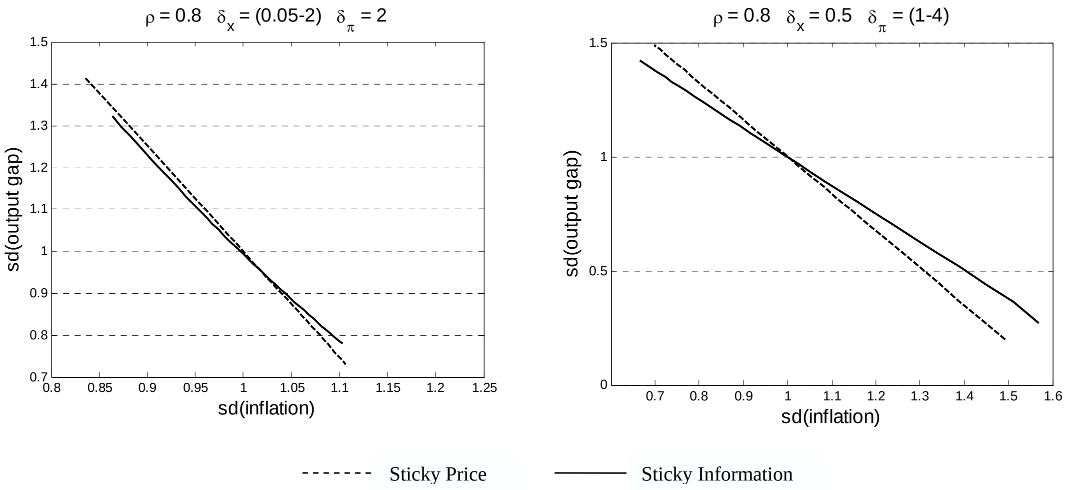

Fig. 3. Efficient policy frontiers for the sticky information and sticky price models when there is a unit cost push shock to the models. When δ_π is fixed at 2, δ_x is changed between 0.05 and 2; and when δ_x is fixed at 0.5, δ_π is changed between 1 and 4.

The impulse responses to a cost-push shock under a given policy with different correlation coefficient are obtained for both models in Figures 4 and 5. In both models, persistence and level of the responses depend on the persistence of the shock term. The persistence and the level of the variables decrease when ρ decreases. The first panels of Figures 4 and 5 show that when ρ becomes zero, that is shock is just a spike, all variables return to their steady state values immediately after the shock in the sticky price model because only future expectations matter in this model; however there are little variations in the periods after the shock in the sticky information model because some firms still use old information.

It can also be seen from Figure 4 that the hump-shaped responses to a cost-push shock in the sticky information model depend on the persistence of the shock. If the shock is not persistent enough then the model produces less hump-shaped dynamic responses. Also, for some low level of ρ, variables might overshoot their long-run levels in the sticky information model; while there are no such overshoots in the sticky price model. Therefore, some of the initial price increase due to the shock is taken back when inflation overshoots and becomes negative in the sticky information model. So the impulse responses to a cost-push shock does not always exhibit a complete "bygones be bygones" in the sticky information model.

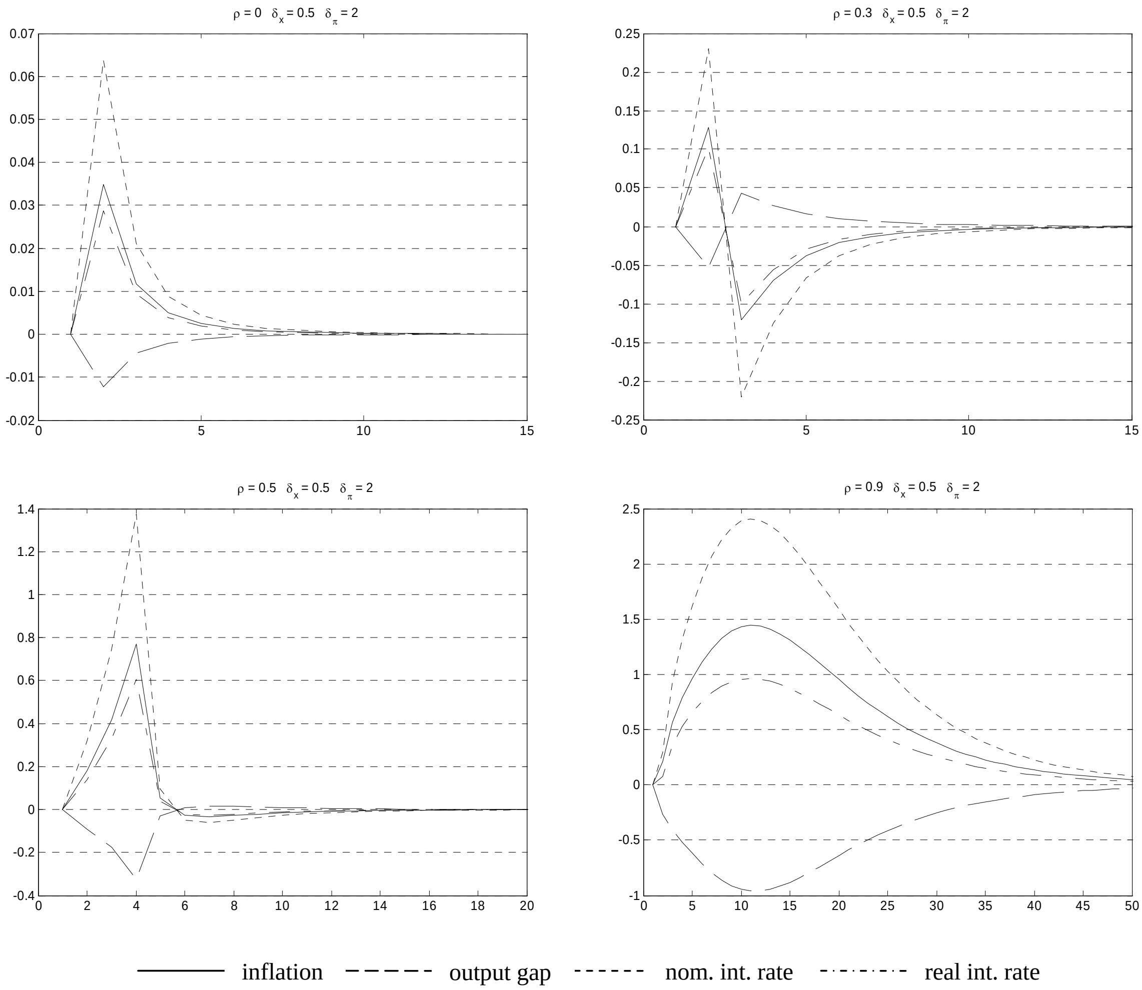

Fig. 4. Impulse responses of the sticky information model to a unit cost push shock for different values of ρ. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

4.3. Sensitivity Analysis

In the above analysis two important structural model parameters are the σ and φ. Since there is no consensus on the values of these parameters, especially on the intertemporal elasticity of substitution as explained above, the sensitivity of the above results to these parameters will be investigated in this section.

In my baseline calibration, σ is taken as 6, which implies a small IES of 0.167, and φ as 0.5. Robustness of the results obtained with this baseline calibration to different parameter set is checked here by assuming $\sigma = 1$ and $\varphi = 1.25$ as in Chari et al. (2000).

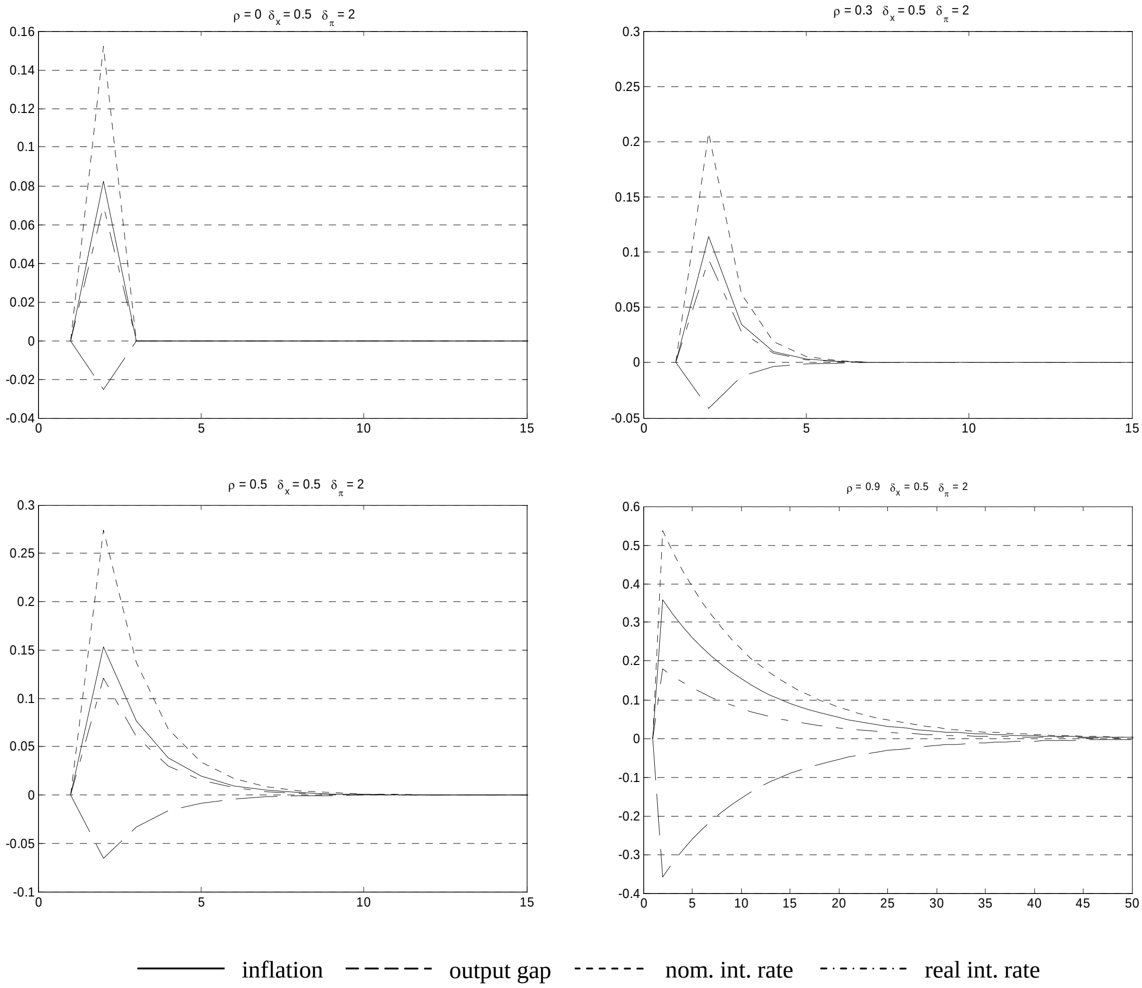

Fig. 5. Impulse responses of the sticky price model to a unit cost push shock for different values of ρ. Cost-push shock is given by the process $u_t = \rho u_{t-1} + \varepsilon_t$.

This calibration of σ implies an IES of 1, which is substantially higher than the IES with the baseline calibration. Also, in this case, the Phillips curve is more flatter than the curve in the baseline case, so changes in inflation rate affect output more.

The above analysis is replicated for $\sigma = 1$ and $\varphi = 1.25$, and Figure 6 gives some sample dynamics for this parameter set in each model. When these responses are compared with the corresponding ones in Figure 1 and 2, it can be seen that level of the variables are affected but the dynamic implications do not change much. The responses of inflation and the output gap to a unit cost-push shock are bigger with this new parameter set. However, the main conclusions and the basic differences between the sticky price and

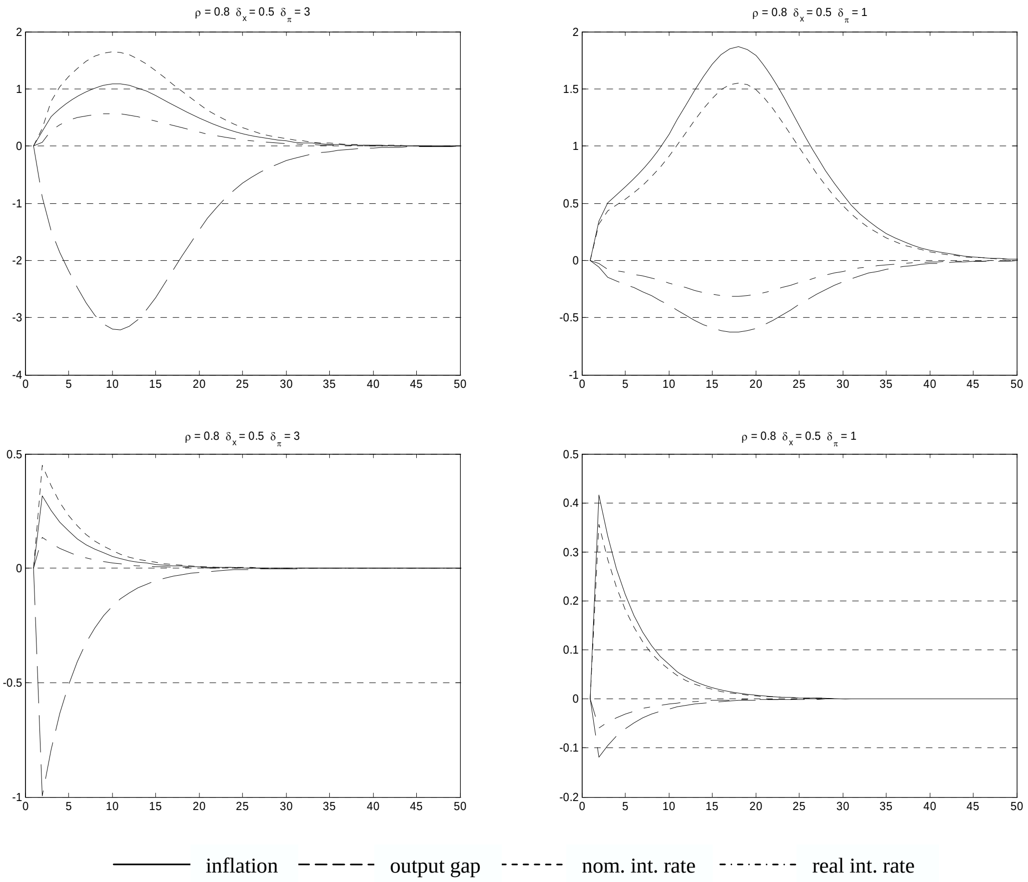

Fig. 6. Impulse responses of models for $\sigma = 1$ and $\varphi = 1.25$. First row is for the sticky information model and the second row is for the sticky price model.

sticky information models obtained with the baseline calibration are still valid here.

5. Conclusions

In this study the sticky information model of price adjustment proposed by Mankiw and Reis is compared with the sticky price model of price adjustment based on Calvo's model in a New Keynesian DSGE framework. Dynamic responses of both models to a unit cost-push shock are examined and compared for different policy alternatives represented by a Taylor-type interest rate rule.

The simulation results show that the monetary policy framework with the sticky information model produces hump-shaped responses, and maximum deviations from steady states occur at some quarters after the shock as observed in data. However, the responses for the sticky price model are not hump-shaped and the maximum deviations occur immediately with the shock contrary to data. It is also observed that the hump-shaped responses to a shock in the sticky information model depend on the persistence of the shock. If the shock is not persistent enough then this model produces less hump-shaped dynamic responses.

The results indicate that variables are more persistent to the cost-push shock in the sticky information model. The persistence and levels of the responses depend on the persistence of the shock term in both models. However, when the persistence of the shock is zero, all variables return to their steady state values immediately after the shock in the sticky price model, while there are some little variations in the sticky information model.

It is observed that the sticky information model produces more stabilization in a sense that standard deviations of the variables are less sensitive to correlation coefficient of the shock when it is large and close to one, while sticky price model stabilizes more when the shock is not very persistent and the correlation coefficient is small and close to zero. According to simulation results dynamic responses are more sensitive to interest rate response to deviation of inflation from its target than the response to deviation of the output gap in both models. Therefore, choosing the policy parameter of interest rate response to inflation deviation is more important in designing monetary policy under a Taylor-type interest rate rule.

When the volatility tradeoffs in both models are compared it is observed that the sticky price model produces somewhat more stable inflation dynamics, while the sticky information model produces more stable output dynamics. The results show that variables may overshoot their long-run level in the sticky information model if the shock is not persistent enough while there are no such overshoots in the sticky price model. Therefore, some of the initial price increase due to the shock is taken back when inflation overshoots and becomes negative in the sticky information model. Also, some sensitivity analysis is performed and it is observed that the basic results from the baseline calibration are preserved for different calibration of some model parameters.

Appendix

A. Solution of the dynamic system for a unit cost-push shock

The rational expectation solutions for inflation and the output gap are found by first writing the system in terms of infinite MA representation of variables, and then equating the coefficients of the ε_τ terms in order to find the moving average coefficients of the output gap β_τ and inflation γ_τ. The first equation of the system (39) for a cost-push shock given the N_t matrix in (40) can be written as

$$E_t\pi_{t+1} = a\pi_t + bx_t + \frac{\sigma}{s}\Big(k\,u_t + (1-\theta)\sum_{k=1}^{\infty}\theta^k E_{t-k}(\pi_{t+1} + \alpha\Delta x_{t+1})\Big), \tag{A.1}$$

where

$$a = \frac{\delta_\pi(\alpha\phi + \alpha(1-\theta))}{s}, \quad b = \frac{(\alpha\phi + \alpha(1-\theta))(\sigma+\delta_x) - \sigma\alpha(1-\theta)}{s}, \quad k = \phi\rho - (1-\theta)(1-\rho).$$

It can be written in infinite order MA representation as

$$\sum_{i=1}^{\infty}\gamma_i\varepsilon_{t+1-i} = a\sum_{i=0}^{\infty}\gamma_i\varepsilon_{t-i} + b\sum_{i=0}^{\infty}\beta_i\varepsilon_{t-i} + \frac{\sigma}{s}\Bigg[k\sum_{i=0}^{\infty}\rho^i\varepsilon_{t-i} + \theta\sum_{i=2}^{\infty}\gamma_i\varepsilon_{t+1-i} - \theta^2\sum_{i=2}^{\infty}\theta^{i-2}\gamma_i\varepsilon_{t+1-i}$$
$$+\alpha\theta\sum_{i=1}^{\infty}(\beta_{i+1}-\beta_i)\varepsilon_{t-i} - \alpha\theta^2\sum_{i=1}^{\infty}\theta^{i-1}(\beta_{i+1}-\beta_i)\varepsilon_{t-i}\Bigg]. \tag{A.2}$$

In the above derivation, the following equalities are used

$$\sum_{k=1}^{\infty}\theta^k E_{t-k}\pi_{t+1} = \frac{\theta}{1-\theta}\sum_{i=2}^{\infty}\gamma_i\varepsilon_{t+1-i} - \frac{\theta^2}{1-\theta}\sum_{i=2}^{\infty}\theta^{i-2}\gamma_i\varepsilon_{t+1-i}\ , \tag{A.3}$$

$$\sum_{k=1}^{\infty}\theta^k E_{t-k}\Delta x_{t+1} = \frac{\theta}{1-\theta}\sum_{i=1}^{\infty}(\beta_{i+1}-\beta_i)\varepsilon_{t-i} - \frac{\theta^2}{1-\theta}\sum_{i=1}^{\infty}\theta^{i-1}(\beta_{i+1}-\beta_i)\varepsilon_{t-i}\ . \tag{A.4}$$

The equations relating the γ_τ and β_τ parameters of inflation and the output gap can be obtained by equating the coefficient of ε_τ terms in (A.2), and they are given by

$$\gamma_1 = a\gamma_0 + b\beta_0 + \frac{\sigma k\rho}{s}\ , \tag{A.5}$$

$$\Big(1 - \frac{\theta(1-\theta^\tau)\sigma}{s}\Big)\gamma_{\tau+1} - \frac{\alpha\theta(1-\theta^\tau)\sigma}{s})\beta_{\tau+1} =$$
$$a\gamma_\tau + \Big(b - \frac{\alpha\theta(1-\theta^\tau)\sigma}{s}\Big)\beta_\tau + \frac{\sigma k}{s}\rho^{\tau+1} \qquad \text{for } \tau > \ 0\ . \quad \text{(A.6)}$$

The second equation from the system (39) is

$$E_t x_{t+1} = c\pi_t + dx_t - \frac{1}{s}\Big(k\,u_t + (1-\theta)\sum_{k=1}^{\infty}\theta^k E_{t-k}(\pi_{t+1} + \alpha\Delta x_{t+1})\Big), \qquad \text{(A.7)}$$

where

$$c = \frac{\delta_\pi\theta}{s}\ , \qquad d = \frac{\theta(\sigma+\delta_x) + \alpha(1-\theta)}{s}\ .$$

This can be written in infinite order MA representation as

$$\sum_{i=1}^{\infty}\beta_i\varepsilon_{t+1-i} = c\sum_{i=0}^{\infty}\gamma_i\varepsilon_{t-i} + d\sum_{i=0}^{\infty}\beta_i\varepsilon_{t-i} - \frac{1}{s}\Big[k\sum_{i=0}^{\infty}\rho^i\varepsilon_{t-i} + \theta\sum_{i=2}^{\infty}\gamma_i\varepsilon_{t+1-i} - \theta^2\sum_{i=2}^{\infty}\theta^{i-2}\gamma_i\varepsilon_{t+1-i}$$
$$+ \alpha\theta\sum_{i=1}^{\infty}(\beta_{i+1}-\beta_i)\varepsilon_{t-i} - \alpha\theta^2\sum_{i=1}^{\infty}\theta^{i-1}(\beta_{i+1}-\beta_i)\varepsilon_{t-i}\Big]\ . \qquad \text{(A.8)}$$

Then, the following equations that relate the parameters of the variables can be obtained

$$\beta_1 = c\gamma_0 + d\beta_0 - \frac{k\rho}{s}\ , \qquad \text{(A.9)}$$

$$\frac{\theta(1-\theta^\tau)}{s}\gamma_{\tau+1} + \Big(1 + \frac{\alpha\theta(1-\theta^\tau)}{s}\Big)\beta_{\tau+1} =$$
$$c\gamma_\tau + \Big(d + \frac{\alpha\theta(1-\theta^\tau)}{s}\Big)\beta_\tau - \frac{k}{s}\rho^{\tau+1} \qquad \text{for } \tau > \ 0\ . \quad \text{(A.10)}$$

Equations (A.6) and (A.10) can be put into the matrix from as

$$\begin{bmatrix} 1-\sigma\zeta & -\alpha\sigma\zeta \\ \zeta & 1+\alpha\zeta \end{bmatrix}\begin{bmatrix}\gamma_{\tau+1}\\ \beta_{\tau+1}\end{bmatrix} = \begin{bmatrix} a & b-\alpha\sigma\zeta \\ c & d+\alpha\zeta\end{bmatrix}\begin{bmatrix}\gamma_\tau \\ \beta_\tau\end{bmatrix} + \begin{bmatrix}\sigma k\rho^{\tau+1}/s \\ -k\rho^{\tau+1}/s\end{bmatrix}\ ,$$

where $\zeta = \theta(1-\theta^\tau)/s$. After some arrangements, it can be written as

$$\begin{bmatrix}\gamma_{\tau+1}\\ \beta_{\tau+1}\end{bmatrix} = Z_\tau\begin{bmatrix}\gamma_\tau\\ \beta_\tau\end{bmatrix} + \begin{bmatrix}\sigma k/\eta s \\ -k/\eta s\end{bmatrix}\rho^{\tau+1}\ , \qquad \text{(A.11)}$$

where $\eta = 1 - \sigma\zeta + \alpha\zeta$, and Z_τ is a 2x2 matrix given by

$$Z_\tau = \begin{bmatrix} \dfrac{\alpha\delta_\pi[\phi + (1-\theta) + \theta(1-\theta^\tau)]}{\eta s} & \dfrac{\alpha\phi\sigma + \alpha\delta_x[\phi + \alpha(1-\theta) + \theta(1-\theta^\tau)]}{\eta s} \\ \dfrac{\delta_\pi\theta^{\tau+1}}{\eta s} & \dfrac{\alpha + \theta^{\tau+1}(\sigma+\delta_x-\alpha)}{\eta s}\end{bmatrix}.$$

Equation (A.11) is a first order deterministic difference equation, and the matrix Z_τ has two positive characteristic roots, such that one is greater than one and the other is less than one for $\delta_\pi \geq 1$. Let's say one root $\lambda_{1\tau} > 1$ and the other root $\lambda_{2\tau} < 1$. The solution to the above system is obtained by finding homogenous and particular solutions.

The homogenous solution is obtained from

$$\begin{bmatrix} \gamma_{\tau+1} \\ \beta_{\tau+1} \end{bmatrix} = Z_\tau \begin{bmatrix} \gamma_\tau \\ \beta_\tau \end{bmatrix} \qquad \text{for } \tau > 0 \,. \tag{A.12}$$

The matrix Z_τ can be decomposed into $Z_\tau = H_\tau \Lambda_\tau H_\tau^{-1}$, where the eigenvectors of Z_τ form the columns of H_τ, and Λ_τ is a diagonal matrix with $\lambda_{1\tau}$ and $\lambda_{2\tau}$ on the diagonal. Then, (A.12) can be written as

$$\begin{bmatrix} \gamma_{\tau+1} \\ \beta_{\tau+1} \end{bmatrix} = H_\tau \Lambda_\tau H_\tau^{-1} \begin{bmatrix} \gamma_\tau \\ \beta_\tau \end{bmatrix}, \qquad \text{and} \qquad H_\tau^{-1} \begin{bmatrix} \gamma_{\tau+1} \\ \beta_{\tau+1} \end{bmatrix} = \Lambda_\tau H_\tau^{-1} \begin{bmatrix} \gamma_\tau \\ \beta_\tau \end{bmatrix}. \tag{A.13}$$

Let, $W_\tau = H_\tau^{-1} \begin{bmatrix} \gamma_\tau \\ \beta_\tau \end{bmatrix}$, then (A.13) reduces to $W_{\tau+1} = \Lambda_\tau W_\tau$, and the following equations can be written

$$W_{1\tau+1} = \lambda_{1\tau} W_{1\tau}, \qquad W_{2\tau+1} = \lambda_{2\tau} W_{2\tau} \tag{A.14}$$

Therefore, W_{11} should be zero in order to have a stationary process of $W_{1\tau}$. Therefore, from the following equation

$$\begin{bmatrix} W_{11} \\ W_{21} \end{bmatrix} = H_\tau^{-1} \begin{bmatrix} \gamma_1 \\ \beta_1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \gamma_1 \\ \beta_1 \end{bmatrix}, \tag{A.15}$$

to have a stable system, the initial conditions for homogenous solution should satisfy

$$h_{11}\gamma_1^H + h_{12}\beta_1^H = 0 \,. \tag{A.16}$$

W_τ can be written for any $\tau > 1$ as

$$\begin{bmatrix} W_{1\tau} \\ W_{2\tau} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \gamma_\tau \\ \beta_\tau \end{bmatrix}.$$

Then, from the first equation of (A.14) and the initial condition, the following equation can be obtained

$$\gamma_{\tau+1}^H = -\frac{h_{12}}{h_{11}}\, \beta_{\tau+1}^H \qquad \text{for } \tau > 0 \,. \tag{A.17}$$

Also, the second equation of (A.14) can be written as

$$h_{21}\gamma^H_{\tau+1} + h_{22}\beta^H_{\tau+1} = \lambda_{2\tau}(h_{21}\gamma^H_{\tau} + h_{22}\beta^H_{\tau}) \ .$$

If (A.17) is used in this equation, one can get

$$\begin{aligned}
&h_{21}(-\frac{h_{12}}{h_{11}})\beta^H_{\tau+1} + h_{22}\beta^H_{\tau+1} = \lambda_{2\tau}(h_{21}(-\frac{h_{12}}{h_{11}})\beta^H_{\tau} + h_{22}\beta^H_{\tau}),\\
&(h_{21}(-\frac{h_{12}}{h_{11}}) + h_{22})\beta^H_{\tau+1} = \lambda_{2\tau}(h_{21}(-\frac{h_{12}}{h_{11}}) + h_{22})\beta^H_{\tau}),\\
&\beta^H_{\tau+1} = \lambda_{2\tau}\beta^H_{\tau} \qquad \text{for } \tau > 0 \ . \qquad \text{(A.18)}
\end{aligned}$$

The particular solution to the non-homogenous part will be in the form of

$$\begin{bmatrix}\gamma^P_\tau\\ \beta^P_\tau\end{bmatrix} = g_\tau\, b^{\tau+1},$$

where g_τ is a 2x1 vector, and b is a scalar. If this is substituted into (A.11) and the coefficients are equated, the following equations are obtained

$$g_\tau\, b^{\tau+2} = Z_\tau g b^{\tau+1} + \begin{bmatrix}\sigma k/\eta s\\ -k/\eta s\end{bmatrix}\rho^{\tau+1},$$

$$g_\tau\, b^{\tau+1}(bI - Z_\tau) = \begin{bmatrix}\sigma k/\eta s\\ -k/\eta s\end{bmatrix}\rho^{\tau+1} \ .$$

So the parameters of the particular solution can be obtained as

$$b = \rho \ ; \qquad g_\tau \ = (\rho I - Z_\tau\ )^{-1}\begin{bmatrix}\sigma k/\eta s\\ -k/\eta s\end{bmatrix}.$$

Thus, the particular solution for $\tau > 0$ will be

$$\begin{bmatrix}\gamma^P_\tau\\ \beta^P_\tau\end{bmatrix} = (\rho I - Z_\tau\ )^{-1}\begin{bmatrix}\sigma k/\eta s\\ -k/\eta s\end{bmatrix}\rho^{\tau+1}. \qquad \text{(A.19)}$$

After having the homogenous and the particular solutions, the complete solution for the system of (A.11) is given by

$$\begin{bmatrix}\gamma_\tau\\ \beta_\tau\end{bmatrix} = \begin{bmatrix}\gamma^H_\tau\\ \beta^H_\tau\end{bmatrix} + \begin{bmatrix}\gamma^P_\tau\\ \beta^P_\tau\end{bmatrix} \qquad \text{for } \tau > 0 \ . \qquad \text{(A.20)}$$

For any γ^H_1 or β^H_1 satisfying the initial conditions (A.16), γ_1 and β_1 can be found by equation (A.20). Then, γ_0 and β_0 can be obtained by using equations (A.5) and (A.9).

Then the remaining parameters of the variables can be obtained from equations (A.17) and (A.18).

Although this process guarantees non-explosive, bounded solutions for the output gap and inflation, it does not produce a unique one. Indeed, an infinite number of bounded solutions can be obtained for the system (A.11), and so for the system (39), given infinite possible combinations satisfying the initial conditions (A.16). This also because there are four unknown parameters $(\gamma_\tau, \gamma_{\tau+1}, \beta_\tau, \beta_{\tau+1})$ for $\tau \geq 0$ and just three equations (A.5, A.9, A.20) to find them. Therefore, one more additional restriction is needed in order to obtain a unique solution. This is obtained from the sticky information Phillips curve given in (34). Since it is valid for every time period, it can be written in terms of general MA representation, and then the first equation relating the initial coefficients γ_0 and β_0 is taken. This equation is given by

$$\gamma_0 = \alpha\phi\beta_0 + \phi \, . \tag{A.21}$$

Writing equations (A.5) and (A.9) in matrix form when γ_1 and β_1 are divided into homogenous and particular parts yields

$$\begin{bmatrix} \gamma_1^H \\ \beta_1^H \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} \gamma_0 \\ \beta_0 \end{bmatrix} + \begin{bmatrix} \sigma k\rho/s - \gamma_1^P \\ -k\rho/s - \beta_1^P \end{bmatrix} . \tag{A.22}$$

The equations (A.16) and (A.21) can be combined with (A.22) in a matrix system as

$$\begin{bmatrix} 1 & 0 & -a & -b \\ 0 & 1 & -c & -d \\ h_{11} & h_{12} & 0 & 0 \\ 0 & 0 & 1 & -\alpha\phi \end{bmatrix} \begin{bmatrix} \gamma_1^H \\ \beta_1^H \\ \gamma_0 \\ \beta_0 \end{bmatrix} = \begin{bmatrix} \sigma k\rho/s - \gamma_1^P \\ -k\rho/s - \beta_1^P \\ 0 \\ \phi \end{bmatrix} . \tag{A.23}$$

Therefore, the parameter values for $\tau = 0$ and homogeneous solutions for $\tau = 1$ can be obtained from the above linear system (A.23), and the remaining ones are calculated by using equations (A.17), (A.18) and (A.19). This gives a unique, bounded, non-explosive rational expectation solution to the system of equation (39) for a cost-push shock.

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