On the Local Determinacy Under Heterogeneous Price Stickiness

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Abstract

Ignoring the heterogeneous price stickiness across the sectors might lead us to a premature conclusion on the local determinacy of the standard New Keynesian models. Equilibrium could still be unique even when the feedback parameter on the inflation in Taylor-type interest rule of a central bank is substantially smaller than one. This consequently suggests that the highly volatile output and inflation in the 70's might have nothing to do with sunspot fluctuations.

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1 Introduction

Let us consider a simple case in which half of the firms in the economy update prices every time period, while the other half set their prices at some steady state values and never update afterward.

In a benchmark New Keynesian framework, there are two different ways to model the frequencies of price adjustments of the economy. A more standard and traditional way would be looking at the economy as a whole, observing that half of the firms updates prices in each period, and then calibrating the frequency of price adjustments to 50%, which is the *representative frequency* that spans all the firms in the economy. An alternative way would be taking the heterogeneities of the frequencies among the firms into account explicitly. The later method is a relatively recent development. A few papers show that it has both normative and positive implications.[1]

In this paper, I show that the different views on the frequencies of price adjustments lead to different conclusions on the local determinacy of rational expectation equilibrium. Let the monetary policy is characterized by Taylor-type interest rules:

$$i_t = \rho_\mu i_{t-1} + (1-\rho_\mu)\left\{\phi_\pi \pi_t + \phi_y x_t\right\} + \mu_t; \quad \rho_\mu \in [0,1),$$

where i_t is nominal interest rate, π_t is inflation, x_t is output gap, and μ_t is monetary policy shock.[2] When the cross-firm distribution of frequencies is calibrated to the empirical distribution reported by Nakamura and Steinsson (2006), the equilibrium is locally unique for all positive values of ϕ_π, the feedback parameter on inflation in the interest rate rule, as long as the other feedback parameter ϕ_y is positive.

The result has an important implication for the recent U.S. history of inflation and output dynamics. Clarida, Gali, and Gertler (2000) (CGG), and Lubik and Schorfheide (2004) find that the declined volatilities of inflation and output from the mid-80's are due to the fact that a change in the feedback parameters in the interest rate rules led to a

[1]For normative implications, see Aoki (?), Beningno (?), and Lee (2006). For positive implications, see Carvalho (2006), Nakamura and Steinsson (2007), and Lee (2007).

[2]I also consider an alternative policy rule in which the nominal interest responds to *expected* output gap and *expected* inflation. The results remain the same.

unique equilbrium and consequently the U.S. economy has not been subject to sunspot fluctuations. I find that their results depend crucially on the assumption that every firm in the economy has the identical degree of nominal rigidity. Even though one accepts the view that there was a systematic change in the policy rule, the change may have nothing to do with eliminating the sunspot fluctuations if one also accepts that homogeneous frequency of prcie adjustments across the firms are only a special case.

The paper is organized as follows. Section 2 presents the model economy. Section 3 revists the special example introduced at the beginning of the paper, and analytically shows that the determinacy of the equilibrium depends on the distribution of the frequencies. In section 3, I consider a general case and provide an intuition why the results are different. Section 4 presents a quantitative analysis on the relation between the volatilities of inflation and output gap and the feedback parameter ϕ_π. Section 5 consludes.

2 The Model

2.1 Households

In this subsection, I describe the households' decision problems and their optimality conditions. There is a representative household that maximizes a discounted sum of utilities:

$$E_0 \sum_{t=0}^{\infty} \beta^t D_t \left[\log C_t - \int \frac{H_t(i)^{1+\varphi}}{1+\varphi} di \right],$$

where C_t household's consumption and $H_t(i)$ is the hours of labor services supplied to firm $i \in (0,1)$. Each firm i in the economy produces a differentiated good i employing a specialized labor input. D_t is intertemporal preference shock. The household's flow budget constraint is given by

$$C_t + \frac{B_t}{P_t} = \frac{(1+i_{t-1})B_{t-1}}{P_t} + \tau_t + \int \frac{W_t(i)H_t(i)}{P_t} di + \Pi_t,$$

where B_t is the nominal bond, τ_t is the government transfer, $W_t(i)$ is the nominal wage rate the household faces from firm i, and Π_t is the economy's aggregate profit.

The household's first order conditions are standard, and are given by

$$1 = \beta(1 + i_t)E_t \left[\left(\frac{D_{t+1}}{D_t} \right) \left(\frac{C_t}{C_{t+1}} \right) \left(\frac{P_t}{P_{t+1}} \right) \right],$$

$$H_t(i)^{\varphi} C_t = \frac{W_{j,t}(i)}{P_t}.$$

2.2 Firm

I describe firms' behavior in this section. The final consumption good Y_t, is produced by a perfectly competitive firm using the intermediate goods, $\{Y_t(i) : i \in (0, 1)\}$ and a CES production technology:

$$Y_t = \left(\int Y_t(i)^{(\theta-1)/\theta} di \right)^{\theta/(\theta-1)}.$$

θ is the elasticity of substitution among the intermediate goods. The corresponding price indexes for the final consumption good is given by

$$P_t = \left(\int P_t(i)^{1-\theta} di \right)^{1/(1-\theta)}.$$

Given Y_t, the optimal demand for $Y_t(i)$ would be

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\theta} Y_t.$$

Every firm i, has a common linear production function:

$$Y_t(i) = S_t H_t(i),$$

where S_t is economy-wide productivity shock (or supply shock). Each firm has potentially different frequency of price adjustments $\alpha\,(i)$. It maximizes discounted profits:

$$\max_{P_t^*(f)} E_t \left\{ \sum_{k=0}^{\infty} (1 - \alpha\,(i))^k \, q_{t,t+k} \left[\frac{P_t^*(i)}{P_{t+k}} Y_{t+k}(i) - \frac{W_{t+k}(i)}{P_{t+k}} \frac{Y_{t+k}(i)}{S_{t+k}} \right] \right\},$$

where

$$q_{t,t+k} \equiv \beta \frac{D_t C_t}{D_{t+k} C_{t+k}}.$$

One special case is the *homogeneous frequency economy* that occurs when $\alpha(i) = \bar{\alpha}$ for all $i \in (0,1)$.

2.3 Government

Government budget constraint is

$$\frac{B_t - (1 + i_{t-1}) B_{t-1}}{P_t} = \tau_t + G_t,$$

where B_t is the government bond supply at time t. Monetary policy is characterized by a Taylor rule:

$$(1 + i_t) = \beta^{-1} \left(\frac{P_t}{P_{t-1}}\right)^{\phi_\pi} \left(\frac{Y_t}{Y_t^N}\right)^{\phi_y} \exp(\mu_t).$$

Y_t^N is the level of output that would be realized when the prices are fully flexible. I assume one particular example of Ricardian fiscal policies:

$$G_t = 0, \quad B_t = 0,$$

Even if this type of fiscal policy assumption is non-trivial for studying determinacy of the equilibrium as pointed out by Leeper (1992) and Sims (1994), I made that assumption for a direct comparison with many existing NK models as well as for simplicity.

3 An Example

In this section, I revisit a simple example stated in the introduction, in which half of the firms in the economy update prices every time period, while the other half set their prices at some steady state values and never update afterward. I first take into account the heterogeneous frequencies explicitely.

The first group of the firms set the price as

$$P_t(i) \equiv P_{1,t} = \bar{P} \quad \forall i \in [0, 0.5).$$

$P_{1,t}$ is the common price chosen by the firms in $[0, 0.5)$, and is equal to $\bar{P}$, a steady state level of prices. The firms in the second group set the prices that satisfy the following first order condition:

$$\left(\frac{P_t(i)}{P_t}\right)^{1+\theta\varphi} \equiv \left(\frac{P_{2,t}}{P_t}\right)^{1+\theta\varphi} = \left(\frac{\theta}{\theta-1}\right)\left(\frac{Y_t}{S_t}\right)^{1+\varphi} \qquad \forall i \in [0.5, 1],$$

where $P_{2,t}$ denotes the the common price chosen by the firms in $[0.5, 1]$.

In the log-linear approximation, we have

$$p_{1,t} = 0 \tag{1}$$

$$p_{2,t} = p_t + \omega\left(y_t - s_t\right), \tag{2}$$

where $\omega \equiv \frac{1+\varphi}{1+\theta\varphi}$. The aggregate price level is given by

$$p_t = 0.5p_{1,t} + 0.5p_{2,t}. \tag{3}$$

Combining (1), (2), and (3) gives the aggregate supply curve (or Phillips curve):

$$p_t = \omega\left(y_t - s_t\right),$$

or equivalently

$$\pi_t = \omega\left(\Delta y_t - \Delta s_t\right). \tag{4}$$

The aggregate demand (or IS curve), and the interest rule are given by

$$y_t = E_t[y_{t+1}] - (i_t - E_t[\pi_{t+1}]) + (d_t - E_t d_{t+1}) \tag{5}$$

$$i_t = \phi_\pi \pi_t + \phi_y y_t + \mu_t \tag{6}$$

The three equations (4), (5), and (6) then characterize the equilibrium path for $\{y_t, \pi_t, i_t\}$ given the exogenous processes $\{\mu_t, s_t, d_t\}$.

Substituting out $\{\pi_t, i_t\}$ gives a second order liner difference equation for y_t :

$$E_t\left[y_{t+1}\right] - \left(1 + \frac{\phi_y + \omega\phi_\pi}{1+\omega}\right) y_t + \left(\frac{\omega\phi_\pi}{1+\omega}\right) y_{t-1} = \chi_t, \tag{7}$$

where χ_t is some linear combination of the exogenous processes. Notice that once we solve for y_t, the other two endogenous variables are determined by (4) and (6). The characteristic polynomial for the difference equation is

$$g(\lambda) = \lambda^2 - \left(1 + \frac{\phi_y + \omega\phi_\pi}{1+\omega}\right)\lambda + \left(\frac{\omega\phi_\pi}{1+\omega}\right).$$

The difference equation gives an unique solution for y_t as long as one root of $g(\lambda)$ is inside the unit circle while the other root is outside of the circle. Note that

$$\begin{aligned} g(-1) &= 2 + \frac{\phi_y + 2\omega\phi_\pi}{1+\omega} > 0 \\ g(1) &= -\frac{\phi_y}{1+\omega} < 0, \end{aligned}$$

as long as ϕ_y is positive and ϕ_π does not have an implausible large negative values.

To summarize, the equilibrium is locally unique for $\forall\left(\phi_\pi, \phi_y\right) \in (0,\infty) \times (0,\infty)$, which is the conventional space for the feedback parameters in the interest rate rule. The result contrasts the case when every firm in the economy is assumed to have an identical frequncy (i.e. $\alpha(i) = \bar{\alpha} = 0.5$ for all $i \in (0,1)$ in this example) because ϕ_π should satisfy the following condition of

$$\phi_\pi > 1 - \frac{(1-\beta)}{\kappa}\phi_y,$$

where $\kappa = \frac{\bar{\alpha}(1-(1-\bar{\alpha})\beta)}{1-\bar{\alpha}}\frac{1+\varphi}{1+\theta\varphi}$, in order to provide an unique equilibrium. The condition implies that, for $\beta = 0.99$ and $\phi_y = 0.5/4$, benchmark parameter values for standard Taylor rule, ϕ_π must be larger than 0.9913.[3]

More generally, this exercise suggests that uniqueness of the equilibrium may depend crucially on assumption of distribution of the frequencies of price adjustments among the firms.

[3]For the other parameters, I set φ to 1, and θ to 6.

4 A More General Case

A practical question to ask at this point is how one should calibrate the distribution of the frequencies $\{\alpha(i) : i \in (0,1)\}$. Since there are continum of the firms and a frequncy could potentially be any value between 0 and 1, α could have a continuous distribution. We then have to keep track of the time path of the cross-firm distributions of outputs and prices $\{y_t(i), p_t(i)\}$, which is unpractical for at least two reasons. First, the state variables becomes infinite dimensional even in the first order approximation so that solving the model is computationally infeasible. Second, there is no empirical research that documents the frequencies at individual firm level and consequently the calibration of the distribution of the frequencies could be based on. As in Carvalho (2006) and in the previous section, I instead discritize the frequencies so that a group of firms shares a same frequency.

Let the elements of the collection $\{\mathcal{I}_j\}_{j=1}^{J}$ are disjoint neighborhoods whose union is the unit interval, that is, $\bigcup\limits_{j=1}^{J} \mathcal{I}_j = (0,1)$. If a firm belongs to a neighborhood $\mathcal{I}_j$ (i.e. $i \in \mathcal{I}_j$), then the frequency of price adjustments of that firm is given by α_j. Then the density function $f(\cdot)$ would be given by $f(\alpha_j) = \mathit{length}(\mathcal{I}_j)$. One important special case is when the degree of nominal rigidities are identical across the firms (i.e. $\alpha(i) = \bar{\alpha}\ \forall i$, or $f(\bar{\alpha}) = 1$). The model then would be identical to the standard NK model often seen in the literautures (see chapter 3 of Woodford (2003) for example).

With the assumption made above, there is no need to keep track of the time path of the distributions of outputs and prices across the entire firms anymore in order to solve for the dynamics of the aggregate variables. It suffices to know the evolutions of the *average outputs* and *average prices* among the firms that belong to the same neighborhood. Accordingly, I define

$$\begin{aligned} Y_{j,t} &\equiv \frac{1}{n_j} \int_{i \in \mathcal{I}_j} Y_t(i) di \\ P_{j,t} &\equiv \frac{1}{n_j} \int_{i \in \mathcal{I}_j} P_t(i) di. \end{aligned}$$

The log-limearized equilibrium conditions are presented below

$$\begin{aligned}
i_t &= \phi_\pi \pi_t + \phi_y x_t + \mu_t && (8) \\
x_t &= E_t[x_{t+1}] - \left(i_t - E_t[\pi_{t+1}] - r_t^N\right) && (9) \\
\pi_t &= \beta E_t\left[\pi_{t+1}\right] + \bar{\kappa} x_t - \sum_{j=1}^{J} \left(f\left(\alpha_j\right)\psi_j\right) p_{j,t}^R && (10) \\
\left(1+\beta+\theta\psi_j\right) p_{j,t}^R &= \beta E_t\left[p_{j,t+1}^R\right] + p_{j,t-1}^R + \kappa_j x_t + \left(\beta E_t\left[\pi_{t+1}\right] - \pi_t\right) && (11)
\end{aligned}$$

where

$$\begin{aligned}
\kappa_j &= \frac{\alpha_j\left(1-\left(1-\alpha_j\right)\beta\right)}{1-\alpha_j}\frac{1+\varphi}{1+\theta\varphi}, \qquad \psi_j = \frac{\alpha_j\left(1-\left(1-\alpha_j\right)\beta\right)}{1-\alpha_j}, \qquad \bar{\kappa} = \sum_{j=1}^{J} f\left(\alpha_j\right)\kappa_j \\
r_t^N &= \left(d_t - E_t\left[d_{t+1}\right]\right) - \left(s_t - E_t\left[s_{t+1}\right]\right).
\end{aligned}$$

The prices with superscript R denote the gap between the average price of the firms that share the same frequency and aggregate price level (i.e. $p_{j,t}^R \equiv p_{j,t} - p_t$), x_t is the output gap, that is $x_t \equiv y_t - y_t^N$, and r_t^N is the natural rate of interest consistent with the model economy.

As illustrated in the previous section, the determinacy of the equilibrium depend on the distribution of frequencies of price adjustments, $f(\alpha)$ for $\alpha = \alpha_1, \alpha_2, ..., \alpha_J$. As a benchmark, I use the empirical distribution from Nakamura and Steinsson (2007). In that case, α has 148 different values on the unit interval, that is $J = 148$. For the single sector case, I use the weighted mean, $\bar{\alpha} = \sum_{j=1}^{J} f\left(\alpha_j\right)\alpha_j$. The distribution are drawn in Figure 1.

A set of standard numerical values are used for the other parameters. I set β, the quarterly discount factor, to be 0.99, φ, the inverse Frisch elasticity of labor supply to 1, and θ, the elasticity of substitution among the different goods, to 6. The exogenous processes are assumed to follow independent AR(1) processes. I set the autoregressive coefficients to 0.9.

Figure 2 shows determinacy and indeterminacy region on (ϕ_x, ϕ_π) space.

The first panel in the figure shows the region in the case of heterogeneous frequencies. Except the case that ϕ_y is exactly equal to zero, the equilibrium is determinate for all values

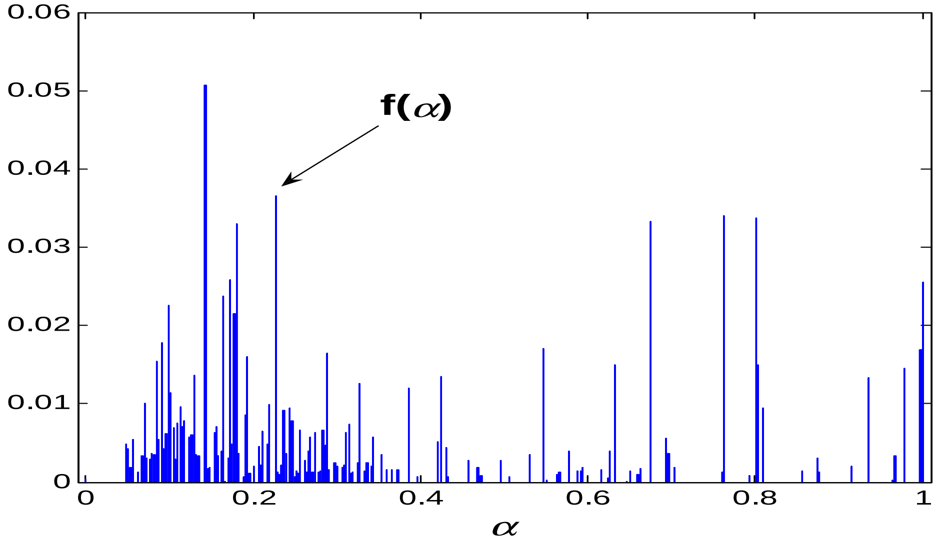

Figure 1: Distribution of Frequencies of Price Adjustments

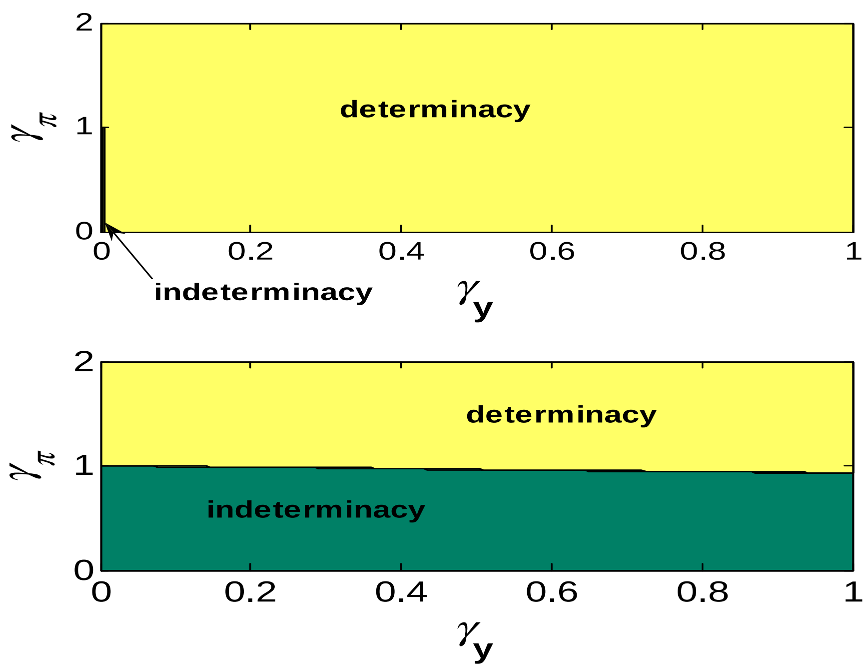

Figure 2: Regions for (in)determinacy for benchmark Taylor rule.

of ϕ_π. Most empirical researches that estimate the Taylor rule report some positive values for ϕ_y, although it is not quite as large as ϕ_π. It is therefore possible to conclude that the volatile inflation in 70's and in early 80's and the subsequent moderation afterwards might have nothing to do with sunspot shocks even if one accepts that ϕ_π was substantially smaller in those days.

The result contrasts the case when one assumes one representative frequency for the entire economy because the second panel shows that the equilibrium is indeterminate and thus subject to sunspot shocks when ϕ_π is roughly less than one.

The different results are due to the endogenous shifter, $\Theta_t \equiv \sum_{j=1}^{J} \left(f\left(\alpha_j\right)\psi_j\right) p_{j,t}^R$, in the Phillps curve.[4] The shifter is positively correlated with both inflation and output gap. Suppose there is an expansionary shock that induces both inflation and output gap to increase. Then the average prices of the firms with flexible prices would be higher than the aggregate price level (i.e. $p_{j,t}^R > 0$), and vice versa for the average prices of the firms with sticky prices (i.e. $p_{j,t}^R < 0$). The endogenous shifter, therefore, has two opposing effects on the aggregate inflation given a certain level of output gap. However, the firms with relatively flexible prices have a greater influence on the aggregate inflation as ψ_j is an increasing function of α_j. Hence the shifter Θ_t moves in the same direction with inflation and output gap. This leads to a shift-out of the Phillps curve as shown in Figure 3. The agents then would expect an greater increase in output gap given an increase in inflation and consequently a greater increase in the nominal interest rate as long as ϕ_y is positive. Therefore, even if ϕ_π is relatively small, the agents would expect the real rate to decrease so that the economy is not subject to sunspot shocks.

The results are robust to some alternative interest rules that are studied in the existing papers. I consider two different policy rules that have the following forms:

$$i_t = \rho_\mu i_{t-1} + \left(1-\rho_\mu\right)\left[\phi_\pi \pi_t + \phi_y x_t\right] + \mu_t \tag{12}$$

$$i_t = \rho_\mu i_{t-1} + \left(1-\rho_\mu\right)\left\{\phi_\pi E_t\left[\pi_{t+1}\right] + \phi_y E_t\left[x_{t+1}\right]\right\} + \mu_t. \tag{13}$$

[4] Carvalho (2006) has developed a very similar model and show that the shifter increases monetary non-neutrality.

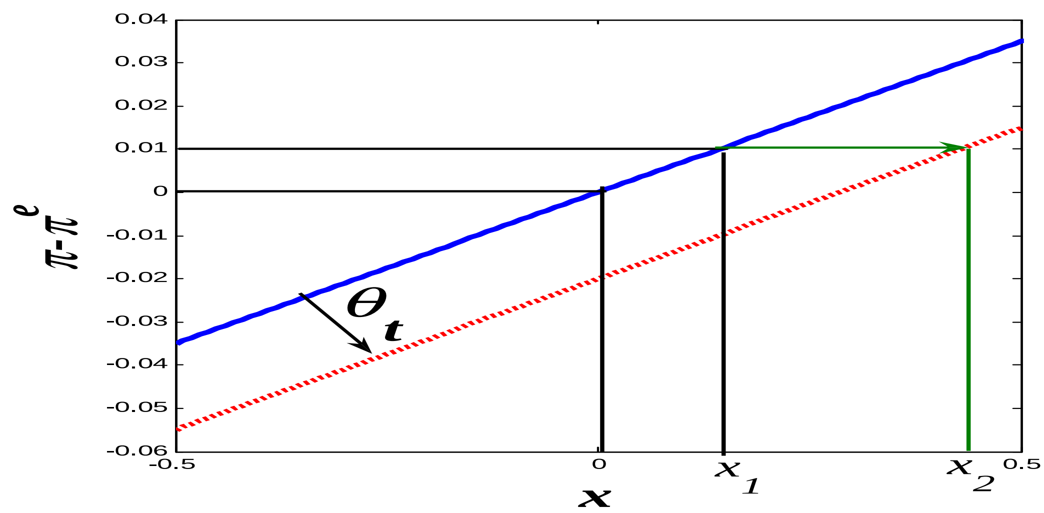

Figure 3: Phillps Curve with Endogenous Shifter.

The regions for determinacy and indeterminacy remain the same as in the standard Taylor rule.

5 Volatility and the Feedback Parameter ϕ_π

The claim that a larger feedback parameter on inflation ϕ_π has been responsible for the moderation is based on the two mechanisms. The first mechanism is the self-fulfilling fluctuation, and it is studied in the previous section. I now investigate the second mechanism. A larger value of ϕ_π would lead to relatively stable inflation and output regardless of indeterminacy.

I use ( ) as the benchmark policy rule, and set ρ_μ and ϕ_y to 0.6 and 0.06 respectively. I then study how standard deviations of inflation and output gap are reduced by increasing ϕ_π from 1 to 2. Following CGG, the experiments are done separately for each structural shock.

Table I shows the results in the case of homogeneous frequency. The standard deviations with $\phi_\pi = 1$ are normalized to one. It confirms the results shown in CGG. Increasing ϕ_π to 2 reduce the volatilities of inflation and output gap substantially. For instance, standard deviation of inflation due to supply shock is only 33% of the same standard deviation with

$\phi_\pi = 1$.

ϕ_π	Supply Shock $std(\pi)$	Supply Shock $std(x)$	Demand Shock $std(\pi)$	Demand Shock $std(x)$
1	1	1	1	1
2	0.33	0.38	0.34	0.38

Table I: Homogeneous Frequency

In the case of heterogeneous frequencies, the importance of the feedback parameter ϕ_π is reduced as shown in Table II.

ϕ_π	Supply Shock $std(\pi)$	Supply Shock $std(x)$	Demand Shock $std(\pi)$	Demand Shock $std(x)$
1	1	1	1	1
2	0.69	0.66	0.73	0.66

Table II: Heterogeneous Frequencies

The results shown in this section is not intended to provide any serious quantitative comparisons of the interest rules with different parameter values. It however provides the insight that there is a possibility that contributions of a change in policy behavior might have been overstated.

6 Evidence for the Endogenous Shifter

6.1 Evidence I (Very Preliminary)

Even though the endogenous shifter Θ_t is implied by the model, it does not mean that the shifter is consistent with data. It is possible that existence of Θ_t is at odd with data.

In this and next subsections, I document two evidences for existence of such a shifter. In fact, an endogenous shifter, that is positively correlated with output gap, helps the Phillps curves to be more consistent with data.

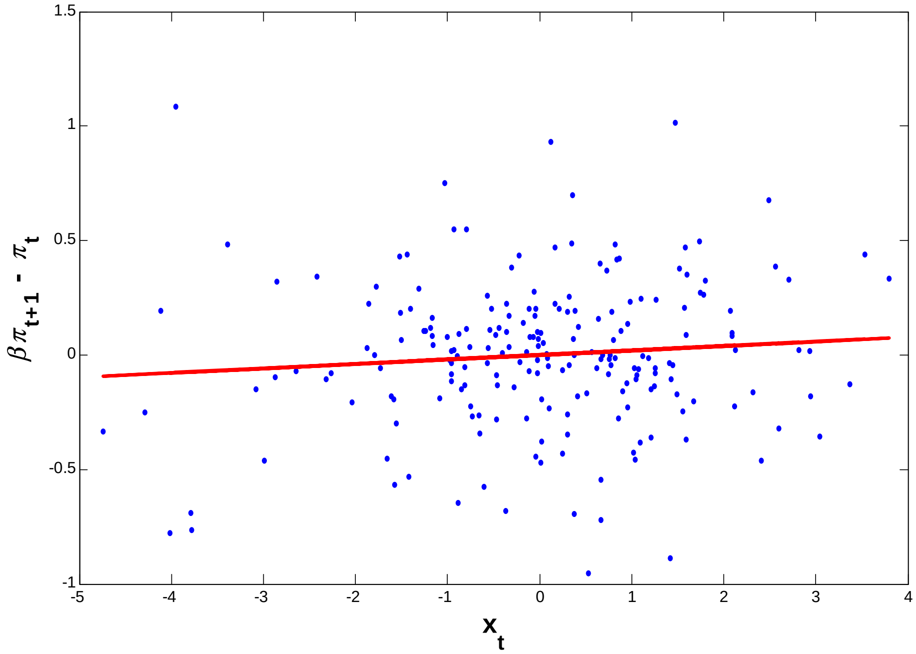

Figure 4: Plots of $(x_t, \tilde{\pi}_{t+1})$, and a fitted line

Let us rewrite the Phillps curve as

$$\beta\pi_{t+1} - \pi_t = -\bar{\kappa}x_t + \Theta_t + \varepsilon_{t+1}, \tag{14}$$

where $\varepsilon_{t+1} \equiv \beta\left(\pi_{t+1} - E_t\pi_{t+1}\right)$ is an expectational error and thus should not be correlated with the variables known at time t. Under the standard NK model without the shifter, we can rewrite ( ) as

$$\tilde{\pi}_{t+1} = \delta x_t + \varepsilon_{t+1},$$

where $\tilde{\pi}_{t+1} \equiv \beta\pi_{t+1} - \pi_t$ and $\delta \equiv -\bar{\kappa}$. Thus the NK model predicts that δ is negative. $\bar{\kappa}$ is approximately 0.071 in the homogeneous frequncy economy if one use the benchmark parameters. However, it seems that there is no clear correlation between $\tilde{\pi}_{t+1}$ and x_t, and if there is any, δ is estimated to be positive using OLS regression ($\delta \approx 0.02$). This has been a puzzle for the NK model.

However, the OLS estimate gives a consistent estimate only when the error terms are uncorrelated with x_t, which would not be true if a *true* data generating process were indeed

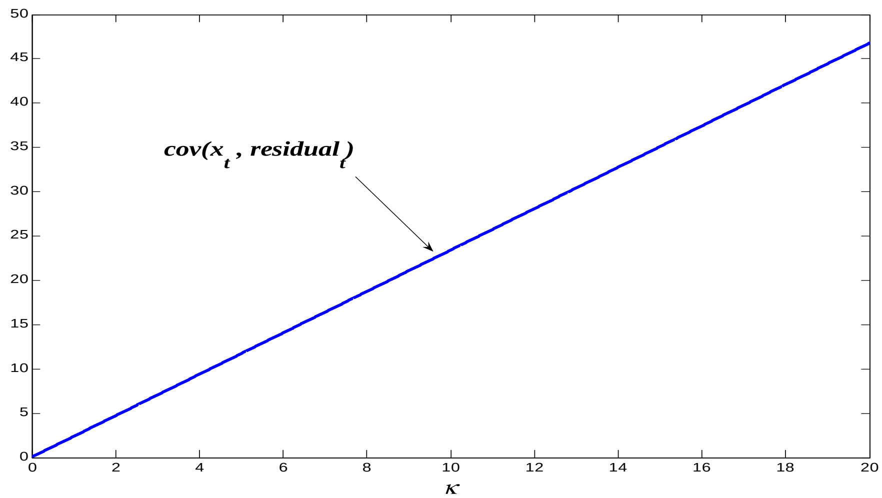

Figure 5: $cov\left(x_t, residual_t\right)$ when a true $\bar{\kappa}$ is positive.

characterized by heterogeneous frequencies. In that case, the error term would include not only the expectational error but also the endogenous shifter. Then the OLS estimate is given by

$$\hat{\delta} = \delta + \frac{T^{-1}\sum_{t=1}^{T} x_t \Theta_t}{T^{-1}\sum_{t=1}^{T} x_t^2} + \frac{T^{-1}\sum_{t=1}^{T} x_t \varepsilon_{t+1}}{T^{-1}\sum_{t=1}^{T} x_t^2},$$

and it converges as follows:

$$\hat{\delta} \longrightarrow \delta + \frac{cov\left(x_t, \Theta_t\right)}{var\left(x_t\right)}.$$

It shows that even if true value of δ is negative as the theory predicts, $\hat{\delta}$ could be positive when $cov\left(x_t, \Theta_t\right)$ is also positive as the thoery *also* predicts. In another word, a positive $\hat{\delta}$ would be consistent with the standard NK theory when the shifter Θ_t were included in the NK Phillps curve.

Indeed for any negative δ (or equivalently any positive $\bar{\kappa}$), the covariance between the regressor x_t and the residual is positive as shown in Figure 5, which suggests that the residual contain some omitted variables that is positively correlated with x_t. While Θ_t is not the only candidate for the omitted variables, it is certainly one of the most natural ones.

To be added

7 Conclusion

To be added

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