ASYMMETRIC EXPECTATION EFFECTS OF REGIME SHIFTS IN MONETARY POLICY

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Abstract. This study answers two substantive questions: (1) Is the magnitude of the expectation effect of regime switching in monetary policy the same across policy regimes? and (2) Is the expectation effect quantitatively important? Using two canonical DSGE models, we show that there exists asymmetry in the expectation effect across regimes. The expectation effect under the dovish policy regime is quantitatively more important than that under the hawkish regime. These results suggest that the possibility of regime shifts in monetary policy can have important effects on rational agents' expectation formation and on equilibrium dynamics. They offer a theoretical explanation for the empirical possibility that a policy shift from the dovish regime to the hawkish regime may not be the main source of substantial reductions in the volatilities of inflation and output.

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> [Lucas (1976)] has expressed the view that it makes no sense to think of the government as conducting one of several possible policies while at the same time assuming that agents remain certain about the policy rule in effect.
>
> *Cooley, LeRoy, and Raymon (1984, p. 468)*

> Explicit modelling of the connection of expectation-formation mechanisms to policy [regime] in an accurately identified model would allow better use of the data.
>
> *Sims (1982, p. 120)*

I. Introduction

Consider monetary policy that follows a Taylor rule, in which the nominal interest rate is adjusted to respond to its own lag and deviations of inflation from its target value and of output from its trend. Suppose there are two monetary policy regimes, where the interest rate responds to inflation more strongly in the second regime (a hawkish regime) than it does in the first regime (a less hawkish or dovish regime). In this policy environment, it is often assumed that when monetary policy enters a particular regime, rational agents naively believe that the regime will prevail indefinitely (see, for example, Clarida, Galí, and Gertler (2000), Lubik and Schorfheide (2004), Boivin and Giannoni (2006)). This assumption, however, does not square well with the rational expectations view in that agents form expectations based on all available information, including possible changes in future policy. This point has been elaborated by Sims (1982), Sargent (1984), Barro (1984), Cooley, LeRoy, and Raymon (1984), and Sims (1987), among others. These authors argue that in an economy where past changes in monetary policy rules are observable and future changes are likely, rational agents' information set should include a probability distribution over possible policy shifts in the future. The difference between equilibrium outcome from a model that ignores probabilistic shifts in future policy regime and that from a model that takes into account such expected changes in regime reflects the key expectation-formation aspect of the Lucas critique, as implied by the antecedent two epigraphs. We call this difference the "expectation effect of regime shifts" in monetary policy.

This paper answers two theoretical questions that are of substantive importance. Is the magnitude of the expectation effect of regime switching the same across policy regimes? Is it quantitatively important? To answer the first question, we obtain closed-form solutions for two dynamic stochastic general equilibrium (DSGE) models, one is a stylized flexible-price model and the other is a canonical sticky-price model. Our analytical results show that no matter whether the price is sticky or not, the expectation effect of regime switching under the hawkish policy regime is smaller than that under the dovish regime. The farther apart the two policy regimes, the larger the difference between the expectation effects under the two regimes.

To quantify the importance of the expectation effect on the dynamics of inflation and output, we simulate the sticky-price model with several sources of plausible frictions. Our simulated results show that the magnitude of the expectation effect depends more on how strong the propagation mechanism is and less on how persistent the prevailing regime is. The stronger the propagation mechanism is, the more impact on inflation and output the expectation of future regime change has. While in theory the expectation effect disappears if the prevailing regime lasts indefinitely, we find that in practice the expectation effect under the dovish policy regime is quantitatively important even if the regime is very persistent.

The asymmetry in the expectation effect of regime switches in monetary policy provides a theoretical insight into the empirical difficulty of finding changes in monetary policy as a main source of the substantial reduction in macroeconomic volatility (Stock and Watson, 2003; Sims and Zha, 2006; Cecchetti, Hooper, Kasman, Schoenholtz, and Watson, 2007). It arises because either the hawkish stance of monetary policy in place or the expectation of switching to the hawkish policy influences agents' inflation expectations in a nonlinear way. As the expectation effect under the dovish regime can considerably alter the dynamics of key macroeconomic variables, caution needs to be taken in interpreting empirical models that are used to fit a subsample that covers only the dovish regime. In the hawkish policy regime, on the other hand, the expectation effect is small even if agents expect that the regime will shift to the dovish regime with a non-trivial probability, as the hawkish policy itself anchors inflation expectations. Thus, even if a newly instituted hawkish regime is not perfectly credible, such as the Volcker disinflation studied by Erceg and Levin (2003) and Goodfriend and King (2005), inflation fluctuations can still be effectively stabilized.

II. Relation to the Literature

There has been a growing strand of literature on Markov-switching rational expectations models.[1] Examples include Andolfatto and Gomme (2003), Leeper and Zha

[1]An interesting issue that remains to be addressed is to what extent the probability of a regime shift is affected by the state of the economy or by the factors other than economic ones. This issue, deserving a separate investigation, is beyond the purpose of this paper.

(2003), Schorfheide (2005), Svensson and Williams (2005), Davig and Leeper (2007a), and Farmer, Waggoner, and Zha (2006). Following this strand of literature, we generalize the standard DSGE model by allowing the possibility of changes in policy regime to be part of the economic information set. We view this kind of regime-switching structural model as a starting point to study the quantitative importance of expectation effects of regime switching in monetary policy, as emphasized by Sims and Zha (2006) and Cecchetti, et al. (2007).

This paper is related to but different from the issues of indeterminacy of the equilibrium. There exists no theoretical result in the literature regarding determinacy vs. indeterminacy for Markov-switching DSGE models, like ours in this paper, that involve lagged endogenous variables such as consumption and inflation.[2] For this reason, we follow McCallum (1983), Svensson and Williams (2005), Farmer, Waggoner, and Zha (2006), and Boivin and Giannoni (2006), among others, and use the minimum-state-variable (MSV) solution as a convenient tool. The dovish regime in this paper does not necessarily correspond to an indeterminate regime; it simply represents a less hawkish regime. The asymmetry exists even if monetary policy in both regimes raises the interest-rate instrument more than one for one in response to inflation, as shown in Section IV.4.

Our paper contributes to the literature by examining the theoretical properties and quantitative importance of the expectation effects of regime shifts in monetary policy. If the expectation effect turns out to be quantitatively unimportant, the equilibrium outcome in a model that ignores changes in future policy regime can be nevertheless a good approximation to the rational expectations equilibrium. If the expectation effect is quantitatively large, however, it is crucial to assess the impacts of the possibility of regime shifts on the equilibrium dynamics of inflation and output. Our finding that the expectation effect can be quantitatively important provides a clear argument for continuing the existing line of research on Markov-switching models that explicitly incorporate a possible switch in policy regime in agents' information set.

III. Theoretical Results

To obtain closed-form analytical results of key properties of the expectation effect, we study two canonical DSGE models, one with flexible prices and one with sticky

[2]In the context of a simple Markov-switching new-Keynesian model that does not involve any lagged endogenous variables, the debate on whether or not there is determinacy of the equilibrium and on how one should restrict one's attention to a subset of equilibria can be found in Davig and Leeper (2007b) and Farmer, Waggoner, and Zha (2008).

prices. Using the closed-form results, we show that our theoretical conclusions hold for both types of models.

III.1. **The flexible-price model.** Consider an endowment economy in which a one-period risk-free nominal bond is traded. The representative agent maximizes the utility

$$\mathrm{E}\sum_{t=0}^{\infty}\beta^t A_t \frac{C_t^{1-\gamma}}{1-\gamma}$$

subject to the budget constraint

$$P_t C_t + B_t = P_t Y_t + R_{t-1} B_{t-1},$$

where C_t denotes consumption, Y_t denotes the endowment, P_t denotes the price level, B_t denotes the agent's holdings of the bond, and R_{t-1} denotes the nominal interest rate between period $t-1$ and t. The parameter $\beta \in (0,1)$ is a subjective discount factor and the parameter $\gamma > 0$ measures the relative risk aversion. The preference shock A_t follows the stationary stochastic process

$$\log A_t = \rho_a \log A_{t-1} + \varepsilon_{at}, \tag{1}$$

where $0 \leq \rho_a < 1$ and ε_{at} is an i.i.d. normal process with mean zero and variance σ_a^2. The endowment follows the stochastic process

$$Y_t = Y_{t-1}\lambda \exp(\nu_t), \quad \nu_t = \rho \nu_{t-1} + \varepsilon_{\nu t}, \tag{2}$$

where $\lambda \geq 1$ measures the average growth rate of the endowment, $\rho_\nu \in (0,1)$ measures the persistence of the endowment shock, and $\varepsilon_{\nu t}$ is an i.i.d. normal process with mean zero and variance σ_ν^2.

The first order condition with respect to the bond holdings is given by

$$\frac{A_t C_t^{-\gamma}}{P_t} = \beta \mathrm{E}_t \frac{A_{t+1} C_{t+1}^{-\gamma}}{P_{t+1}} R_t, \tag{3}$$

which describes the trade-off between spending a dollar today for current consumption and saving a dollar for future consumption.

Monetary policy follows the interest rate rule

$$R_t = \kappa \left(\frac{\pi_t}{\pi^*}\right)^{\phi_{s_t}}, \tag{4}$$

where $\pi_t = P_t / P_{t-1}$ is the inflation rate, π^* denotes the inflation target, s_t denotes the realization of monetary policy regime in period t, ϕ_{s_t} is a regime-dependent parameter that measures the aggressiveness of monetary policy against deviations of inflation from its target, and κ is a constant. Monetary policy regime follows a Markov-switching process between two states: a dovish regime characterized by $s_t = 1$ and $0 \leq \phi_1 < 1$

and a hawkish regime by $s_t = 2$ and $\phi_2 > 1$. The transition probability matrix $Q = [q_{ij}]$ is a 2×2 matrix with $q_{ij} = \text{Prob}(s_{t+1} = i | s_t = j)$. Each column of Q sums up to 1 so that $q_{21} = 1 - q_{11}$ and $q_{12} = 1 - q_{22}$.

Market clearing implies that $C_t = Y_t$ and $B_t = 0$ for all t. Using the goods market clearing condition, we can rewrite the intertemporal Euler equation as

$$\beta \text{E}_t \frac{A_{t+1}}{A_t} \left(\frac{y_{t+1}}{y_t} \right)^{-\gamma} \frac{R_t}{\pi_{t+1}} = 1. \tag{5}$$

Thus, higher consumption (or income) growth requires a higher real interest rate.

III.1.1. *Steady state and equilibrium dynamics.* Given the stochastic process (2) for the endowment, an equilibrium in this economy is summarized by the Euler equation (5) and the monetary policy rule (4). The variables of interest include the inflation rate π_t and the nominal interest rate R_t.

A steady state is an equilibrium in which all shocks are shut off (i.e., $\varepsilon_{at} = \varepsilon_{\nu t} = 0$ for all t). The Euler equation implies that, in the steady state, we have

$$\frac{R}{\pi} = \frac{\lambda^\gamma}{\beta}.$$

Let $\kappa = \frac{\lambda^\gamma}{\beta} \pi^*$. It follows from the Euler equation (5) and the interest rate rule (4) that the steady-state solution is

$$\pi = \pi^*, \quad R = \frac{\lambda^\gamma}{\beta} \pi^*.$$

Although monetary policy switches between the two regimes, the steady-state solution does not depend on policy regime and thus allows us to log-linearize the equilibrium conditions around the constant steady state.

Log-linearizing the Euler equation (5) around the steady state results in

$$\hat{R}_t = \text{E}_t \hat{\pi}_{t+1} + \gamma(1 - \rho_a)\hat{a}_t + \gamma \rho_\nu \nu_t, \tag{6}$$

where $\hat{R}_t$ and $\hat{\pi}_t$ denote the log-deviations of the nominal interest rate and the inflation rate from steady state and $\hat{a}_t = \log A_t$. Thus, a positive preference shock and a positive income shock both serve to raise the real interest rate. A rise in $\hat{a}_t$ implies a stronger desire for consumption relative to saving and thus interest rate rises; a rise in ν_t leads to a rise in expected consumption growth and thus a rise in the interest rate as well. Log-linearizing the interest rate rule (4) around the deterministic steady state leads to

$$\hat{R}_t = \phi_{s_t} \hat{\pi}_t. \tag{7}$$

Combining (6) and (7), we obtain the single equation that describes inflation dynamics:

$$\phi_{s_t} \hat{\pi}_t = \text{E}_t \hat{\pi}_{t+1} + \gamma(1 - \rho_a)\hat{a}_t + \gamma \rho_\nu \nu_t, \quad s_t \in \{1, 2\}. \tag{8}$$

In what follows, we focus on the responses of inflation to the preference shock; the responses of inflation to the income shock are qualitatively identical.[3]

III.1.2. *The equilibrium solution.* The state variable in the simple model (8) is the preference shock $\hat{a}_t$. Thus the solution takes the form $\pi_t = \alpha_{s_t}\hat{a}_t$, where α_{s_t} is to be solved for $s_t \in \{1, 2\}$. Denote

$$A = \begin{bmatrix} \phi_1 - \rho_a q_{11} & -\rho_a q_{21} \\ -\rho_a q_{12} & \phi_2 - \rho_a q_{22} \end{bmatrix}.$$

The following proposition gives the closed-form solution.

Proposition 1. The MSV solution to the regime-switching model (8) is given by

$$\hat{\pi}_t = \alpha_{s_t}\hat{a}_t, \quad s_t \in \{1, 2\},$$

where

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = A^{-1} \begin{bmatrix} \gamma(1-\rho_a) \\ \gamma(1-\rho_a) \end{bmatrix}, \tag{9}$$

with the implicit assumption that the matrix A is invertible.

Proof. See Appendix B.1. □

The solution represented by (9) implies that the volatility, measured by the standard deviation of inflation, is given by

$$v_{\pi,1} = \frac{|\alpha_1|}{\sqrt{1-\rho_a^2}}\sigma_a, \quad v_{\pi,2} = \frac{|\alpha_2|}{\sqrt{1-\rho_a^2}}\sigma_a.$$

The following proposition establishes that the volatility of inflation in the dovish regime decreases with the probability of switching to the hawkish regime and that the volatility of inflation in the hawkish regime increases with the probability of switching to the dovish regime. Thus, the expectation of regime switch affects inflation dynamics.

Proposition 2. Assume that A is positive definite. Then the MSV solution given by (9) has the property that $\alpha_j > 0$ for $j \in \{1, 2\}$ and that

$$\frac{\partial v_{\pi,1}}{\partial q_{21}} < 0, \quad \frac{\partial v_{\pi,2}}{\partial q_{12}} > 0. \tag{10}$$

Proof. See Appendix B.2. □

[3] See an earlier draft of the paper Liu, Waggoner, and Zha (2007). Note that if the endowment follows a pure random walk process, i.e., if $\rho_\nu = 0$, then the income shock has no effect on inflation as it does not affect the intertemporal decision.

III.1.3. *Expectation effects.* The solution (9) takes into account possible switches of future policy regime. This solution in general differs from that obtained under the simplifying assumption that agents believe that the current regime will continue permanently. The difference between these two solutions is what we call the expectation effect of regime switching.

To examine the underlying forces that drive the expectation effect, we consider the solution that rules out regime shifts in future policy, which is equivalent to solving the following model

$$\phi_j \hat{\pi}_t = \mathrm{E}_t \hat{\pi}_{t+1} + \gamma(1-\rho_a)\hat{a}_t, \tag{11}$$

where ϕ_j ($j = 1, 2$) does not depend on time. The equilibrium condition (11) is a special case of the condition (8) with $q_{11} = 1$ for $j = 1$ and with $q_{22} = 1$ for $j = 2$. The solution to (11) is given by the following proposition.

Proposition 3. The MSV solution to the model described in (11) is

$$\hat{\pi}_t = \bar{\alpha}_j \hat{a}_t, \quad \bar{\alpha}_j = \frac{\gamma(1-\rho_a)}{\phi_j - \rho_a}, \quad j \in \{1, 2\}, \tag{12}$$

where it is assumed that $\phi_j \neq \rho_a$.

Proof. See Appendix B.3. □

The solution represented by (12) implies that the volatility of inflation under the assumption that rules out changes in future policy regime is given by

$$\bar{v}_{\pi,1} = \frac{|\bar{\alpha}_1|}{\sqrt{1-\rho_a^2}}\sigma_a, \quad \bar{v}_{\pi,2} = \frac{|\bar{\alpha}_2|}{\sqrt{1-\rho_a^2}}\sigma_a.$$

The expectation effect of regime switches can be measured by the magnitude $|\alpha_j - \bar{\alpha}_j|$ for $j = 1, 2$. Because $\bar{\alpha}_j$ does not depend on transition probabilities, Proposition 2 implies that the less persistent the regime j is, the more significant the expectation effect $|\alpha_j - \bar{\alpha}_j|$ becomes.

III.1.4. *Asymmetry.* As one can see from (9), α_j is nonlinear in the model parameters. This nonlinearity implies that when the probabilities of switching are the same for both regimes (i.e., when $q_{11} = q_{22}$), the expectation effect may not be symmetric across the two regimes. This result is formally stated in the following proposition.

Proposition 4. Assume that $q_{11} = q_{22}$. If $\phi_1 > \rho_a$ and $\alpha_1, \alpha_2 > 0$, then

$$\frac{\bar{v}_{\pi,1} - v_{\pi,1}}{v_{\pi,2} - \bar{v}_{\pi,2}} = \frac{\phi_2 - \rho_a}{\phi_1 - \rho_a} > 1. \tag{13}$$

Proof. See Appendix B.4. □

In the dovish regime, as we show in Proposition 2, the expectation of switching to the hawkish regime stabilizes inflation fluctuations; in the hawkish regime, the expectation of switching to the dovish regime destabilizes inflation. Proposition 4 establishes that the stabilizing effect in the dovish regime exceeds the destabilizing effect in the hawkish regime. Moreover, the expectation effect becomes more asymmetric if the shock is more persistent, if monetary policy takes a stronger hawkish stance against inflation in the hawkish regime, or if policy is less responsive to inflation in the dovish regime. Since these results are derived from a simple model with flexible prices, we examine below whether or not these results survive in models with nominal and real rigidities.

III.2. **The sticky-price model.** We have shown that, in the flexible-price model, the possibility of regime-switching in monetary policy generates expectation effects that stabilize inflation in the dovish regime and destabilize it in the hawkish regime. Furthermore, the expectation effect can be asymmetric across regimes: the stabilizing effect of regime shifts tends to be larger in magnitude than the destabilizing effect. Do these results hold for economies with richer and more realistic equilibrium dynamics? To answer this question, we study a stylized sticky-price model.

The model economy is populated by a continuum of infinitely-lived identical households, each endowed with a unit of labor time; and a continuum of firms, each producing a differentiated product using labor as the input. The representative household consumes a composite good, which is produced in a perfectly competitive aggregation sector using all differentiated products as inputs. In each period, rational agents observe the realization of shocks and the monetary policy regime before making optimizing decisions.

The representative household's utility function is given by

$$\mathrm{E}\sum_{t=0}^{\infty}\beta^t A_t\left\{\log(C_t - b\bar{C}_{t-1}) - \frac{\Psi}{1+\xi}L_t^{1+\xi}\right\} \tag{14}$$

subject to the sequence of budget constraints

$$\bar{P}_t C_t + \mathrm{E}_t D_{t,t+1}B_{t+1} \leq W_t L_t + B_t + \Pi_t, \tag{15}$$

for $t \geq 0$. In the expressions above, C_t denotes consumption, $\bar{C}_{t-1}$ is the lagged aggregate consumption, $b \geq 0$ measures the importance of habit formation, L_t denotes labor, A_t denotes the preference shock, B_{t+1} denotes a state-contingent nominal bond that represents a claim to one dollar in a particular event in period $t+1$ and costs $D_{t,t+1}$ dollars in period t, $\bar{P}_t$ denotes the price level, W_t denotes the nominal wage, and Π_t denotes the profit share. The term E is an expectation operator, the parameter

$\beta \in (0,1)$ is a subjective discount factor, ξ is the inverse Frisch elasticity of labor supply, and Ψ is the relative weight of leisure in the utility function. The preference shock A_t follows the stochastic process as in (1).

The final consumption good is produced in the perfectly competitive aggregation sector using differentiated intermediate goods as inputs, with the Dixit-Stiglitz aggregation technology

$$C_t = \left[\int_0^1 Y_t(j)^{\frac{\theta_t - 1}{\theta_t}} dj \right]^{\frac{\theta_t}{\theta_t - 1}}, \tag{16}$$

where $Y_t(j)$ denotes the type-j intermediate good and $\theta_t > 1$ is the elasticity of substitution between the differentiated intermediate goods. The price markup is measured by $\mu_t = \theta_t/(\theta_t - 1)$, which follows the stationary stochastic process

$$\ln \mu_t = (1 - \rho_\mu) \ln \mu + \rho_\mu \ln \mu_{t-1} + \varepsilon_{\mu t}, \tag{17}$$

where μ denotes the steady-state markup, ρ_μ measures the persistence of the markup shock, and $\varepsilon_{\mu t}$ follows an i.i.d. normal process with mean zero and variance σ_μ^2.

Cost-minimizing implies that

$$Y_t^d(j) = \left(\frac{P_t(j)}{\bar{P}_t} \right)^{-\theta_t} C_t. \tag{18}$$

Zero-profit implies that the price index $\bar{P}_t$ is related to the prices $P_t(j)$ of differentiated goods through

$$\bar{P}_t = \left[\int_0^1 P_t(j)^{1-\theta_t} \right]^{\frac{1}{1-\theta_t}}. \tag{19}$$

The production function for firm $j \in [0,1]$ is given by

$$Y_t(j) = Z_t L_t(j)^\alpha. \tag{20}$$

Following Chari, Kehoe, and McGrattan (2000), we assume that firms' production requires both labor and firm-specific factors (such as land or capital stock that is inelastically supplied) so that $\alpha \in (0,1]$. The technology shock Z_t follows the stochastic process

$$Z_t = Z_{t-1} \lambda \nu_t, \tag{21}$$

where λ measures the deterministic trend of Z_t and ν_t is a stochastic component of Z_t. The stochastic component follows the stationary process

$$\log \nu_t = \rho_\nu \log \nu_{t-1} + \varepsilon_{\nu t}, \tag{22}$$

where $\rho_\nu \in (0,1)$ and $\varepsilon_{\nu t}$ is a white-noise process with mean zero and variance σ_ν^2.

Firms in the intermediate good sector are price-takers in the input market and monopolistic competitors in the product markets. They set prices for their differentiated products in a staggered fashion. Following Calvo (1983), we assume that in each period, each firm receives a random i.i.d. signal that enables the firm to set a new price. The probability that a firm cannot adjust its price is η. By the law of large numbers, a fraction $1-\eta$ of firms in a given period can optimize their pricing decisions while the remaining firms cannot. Following Woodford (2003), CEE (2005), and Smets and Wouters (2007), we allow a fraction ι of firms that cannot re-optimize their pricing decisions to index their prices to the overall price inflation realized in the past period. If the firm j cannot set a new price, its price is automatically updated according to

$$P_t(j) = \pi_{t-1}^{\iota}\pi^{1-\iota}P_{t-1}(j), \tag{23}$$

where $\pi_t = \bar{P}_t/\bar{P}_{t-1}$ is the inflation rate between $t-1$ and t, π is the steady-state inflation rate, and ι measures the degree of indexation. If the firm j can set a new price, it chooses $P_t(j)$ to maximize its expected discounted dividend flows given by

$$\mathrm{E}_t \sum_{i=0}^{\infty} \eta^i D_{t,t+i}\left[P_t(j)\chi_{t,t+i}Y_{t+i}^d(j) - W_{t+i}(j)\left(\frac{Y_{t+i}^d(j)}{Z_{t+1}}\right)^{1/\alpha}\right] \tag{24}$$

subject to the demand schedule (18). The term $D_{t,t+i}$ is the period-t present value of a dollar in a future state in period $t+i$ and the term $\chi_{t,t+i}$ comes from the price-updating rule (23) and is given by

$$\chi_{t,t+i} = \begin{cases} \pi_{t+i-1}^{\iota}\pi_{t+i-2}^{\iota}\cdots\pi_t^{\iota}\pi^{(1-\iota)i} & \text{if } i \geq 1, \\ 1 & \text{if } i = 0. \end{cases} \tag{25}$$

The monetary authority follows the interest-rate rule

$$R_t = \kappa_{s_t} R_{t-1}^{\rho_{r,s_t}}\left[\left(\frac{\pi_t}{\pi^*}\right)^{\phi_{\pi,s_t}} \tilde{Y}_t^{\phi_{y,s_t}}\right]^{1-\rho_{r,s_t}} e^{\varepsilon_{rt}}, \tag{26}$$

where $\tilde{Y}_t = Y_t/Z_t$ is detrended output, π^* is the target rate of inflation, and the policy parameters κ_{s_t}, ρ_{r,s_t}, ϕ_{π,s_t}, and ϕ_{y,s_t} depend on the regime s_t. The term ε_{rt} is a shock to monetary policy and follows an i.i.d. normal process with mean zero and variance σ_r^2. All the structural shocks ε_{rt}, ε_{at}, $\varepsilon_{\mu t}$, and $\varepsilon_{\nu t}$ are assumed to be mutually independent.

Given monetary policy, an *equilibrium* in this economy consists of prices and allocations such that (i) taking prices as given, the representative household's allocations solve its utility maximizing problem; (ii) taking all prices but its own as given, each firm's allocation and price solve its profit maximizing problem; (iii) markets clear for bond, money balances, labor, and composite final goods.

In Appendix A, we derive the stationary equilibrium conditions and show that although the monetary policy rule is regime dependent, the steady state does not vary with the policy regime. We characterize the equilibrium dynamics by first-order approximations to the stationary equilibrium conditions around the deterministic steady state.

Log-linearizing the optimal pricing decision rule leads to the Phillips curve relation

$$\begin{aligned}\hat{\pi}_t - \iota\hat{\pi}_{t-1} &= \beta \mathrm{E}_t(\hat{\pi}_{t+1} - \iota\hat{\pi}_t) \\ &+\psi\left[\frac{\xi+1}{\alpha}\tilde{y}_t + \frac{b}{\lambda-b}(\tilde{y}_t - \tilde{y}_{t-1} + \hat{\nu}_t)\right] + \psi\hat{\mu}_t, \qquad (27)\end{aligned}$$

where

$$\psi = \frac{(1-\beta\bar{\eta})(1-\eta)}{\eta}\frac{1}{1+\theta(1-\alpha)/\alpha},$$

$\hat{\pi}_t$ denotes the inflation rate, $\tilde{y}_t$ denotes detrended output, $\hat{\nu}_t$ denotes the productivity shock, and $\hat{\mu}_t$ denotes the markup shock.

Log-linearizing the intertemporal Euler equation leads to the IS-curve relation

$$\begin{aligned}&\mathrm{E}_t\tilde{y}_{t+1} - \frac{\lambda+b}{\lambda}\tilde{y}_t + \frac{b}{\lambda}\tilde{y}_{t-1} = \\ &\left(1-\frac{b}{\lambda}\right)\left(\hat{R}_t - \mathrm{E}_t\hat{\pi}_{t+1}\right) + \left(\frac{b}{\lambda} - \rho_\nu\right)\hat{\nu}_t - \frac{(\lambda-b)(1-\rho_a)}{\lambda}\hat{a}_t, \qquad (28)\end{aligned}$$

where $\hat{R}_t = \log(R_t/R)$ denotes the nominal interest rate.

Finally, the first-order approximation to the interest rate rule leads to

$$\hat{R}_t = \rho_{r,s_t}\hat{R}_{t-1} + (1-\rho_{r,s_t})[\phi_{\pi,s_t}\hat{\pi}_t + \phi_{y,s_t}\tilde{y}_t] + \varepsilon_{rt}. \qquad (29)$$

To be able to derive closed-form results about expectation effects of regime switching for this model, we let $b = \iota = 0$, $\alpha = 1$, $\rho_{r,s_t} = 0$, and $\phi_{y,s_t} = 0$ and concentrate on dynamic responses of inflation to the preference shock.[4] In Section IV we simulated results to analyze a more general case.

One can show that, by restricting attention to the preference shock, Equations (27), (28), and (29) can be simplified to the three standard new-Keynesian equations:

$$\begin{aligned}\hat{\pi}_t &= \beta\mathrm{E}_t\hat{\pi}_{t+1} + \psi(1+\xi)\tilde{y}_t, \qquad (30)\\ \tilde{y}_t &= \mathrm{E}_t\tilde{y}_{t+1} - [\hat{R}_t - \mathrm{E}_t\hat{\pi}_{t+1}] + (1-\rho_a)\hat{a}_t, \qquad (31)\\ \hat{R}_t &= \phi_{s_t}\hat{\pi}_t. \qquad (32)\end{aligned}$$

[4]Our theoretical results hold for dynamic responses to other shocks.

Substituting out the variables $\tilde{y}_t$ and $\hat{R}_t$ by using (30) and (32), we obtain the second-order difference equation

$$\beta\,\mathrm{E}_t\hat{\pi}_{t+2} - (1+\beta+\kappa)\,\mathrm{E}_t\hat{\pi}_{t+1} + (1+\kappa\phi_{s_t})\hat{\pi}_t = \kappa(1-\rho_a)\hat{a}_t, \tag{33}$$

where the parameter $\kappa = \psi(1+\xi)$.

Since $\hat{a}_t$ is the only state variable, the solution takes the form $\hat{\pi}_t = \gamma_{s_t}\hat{a}_t$, where γ_{s_t} is to be solved for $s_t \in \{1,2\}$. The following proposition summarizes the solution in the sticky-price model.

Proposition 5. The MSV solution to the regime-switching model (33) is given by

$$\hat{\pi}_t = \gamma_{s_t}\hat{a}_t, \quad s_t \in \{1,2\}$$

where

$$\begin{bmatrix}\gamma_1\\ \gamma_2\end{bmatrix} = A^{-1}\begin{bmatrix}\kappa(1-\rho_a)\\ \kappa(1-\rho_a)\end{bmatrix}, \tag{34}$$

where the matrix A, defined below, is assumed to be invertible.

$$A = \begin{bmatrix}\kappa(\phi_1-\rho_a q_{11}) + (1-\rho_a q_{11})(1-\beta\rho_a q_{11}) & -\rho_a q_{21}[1-\beta\rho_a q_{22}+\beta(1-\rho_a q_{11})+\kappa]\\ -\rho_a q_{12}[1-\beta\rho_a q_{11}+\beta(1-\rho_a q_{22})+\kappa] & \kappa(\phi_2-\rho_a q_{22}) + (1-\rho_a q_{22})(1-\beta\rho_a q_{22})\end{bmatrix}$$

Proof. See Appendix B.5. □

To obtain the expectation effect of regime shifts, we compare the solution (34) with the constant-regime solution. The next proposition establishes the constant-regime solution.

Proposition 6. The MSV solution to the model in which agents expect the particular regime j to last forever is given by

$$\hat{\pi}_t = \bar{\gamma}_j\hat{a}_t, \quad \bar{\gamma}_j = \frac{\kappa(1-\rho_a)}{(1-\rho_a)(1-\beta\rho_a)+\kappa(\phi_j-\rho_a)}, \quad j \in \{1,2\} \tag{35}$$

where we assume that $\kappa(\phi_1-\rho_a) > -(1-\rho_a)(1-\beta\rho_a)$ so that $\bar{\gamma}_j > 0$ for $j \in \{1,2\}$.

Proof. The constant-regime solution is a special case of the model (33) with $q_{ii} = 1$ for $i \in \{1,2\}$. □

The following two propositions establish the existence of the expectation effect. In particular, the volatility of inflation in the dovish regime decreases with the probability of switching to the hawkish regime, while the volatility in the hawkish regime increases with the probability of switching to the dovish regime. More formally, we define the volatilities of inflation under different scenarios as follows:

$$v_{\pi,1} = \frac{\gamma_1}{\sqrt{1-\rho_a^2}}\sigma_a, \quad v_{\pi,2} = \frac{\gamma_2}{\sqrt{1-\rho_a^2}}\sigma_a,$$

$$\bar{v}_{\pi,1} = \frac{\bar{\gamma}_1}{\sqrt{1-\rho_a^2}}\sigma_a, \quad \bar{v}_{\pi,2} = \frac{\bar{\gamma}_2}{\sqrt{1-\rho_a^2}}\sigma_a.$$

Proposition 7. The MSV solution in (34) has the property that $\gamma_j > 0$ for $j \in \{1, 2\}$ and that

$$\frac{\partial v_{\pi,1}}{\partial q_{21}} < 0, \quad \frac{\partial v_{\pi,2}}{\partial q_{12}} > 0. \tag{36}$$

Proof. See Appendix B.6. □

Proposition 8. $\bar{v}_{\pi,1} > v_{\pi,1}$ and $\bar{v}_{\pi,2} < v_{\pi,2}$.

Proof. The proof follows directly from Appendix B.6. □

We have established that the expectation effect can generate inflation dynamics different from those implied by the constant-parameter version of the model. We now show that the expectation effect is asymmetric even when the probability of switching is the same for both regimes (i.e., $q_{11} = q_{22}$). The result is summarized as follows.

Proposition 9. Assume that $q_{11} = q_{22}$. We have

$$\frac{\bar{v}_{\pi,1} - v_{\pi,1}}{v_{\pi,2} - \bar{v}_{\pi,2}} = \frac{(1-\rho_a)(1-\beta\rho_a) + \kappa(\phi_2 - \rho_a)}{(1-\rho_a)(1-\beta\rho_a) + \kappa(\phi_1 - \rho_a)} > 1. \tag{37}$$

Thus, as in the flexible-price model, the expectation effects in the sticky-price model here stabilize inflation fluctuations in the dovish regime and magnify inflation fluctuations in the hawkish regime. The stabilizing effect exceeds the magnifying effect.

IV. Quantitative Importance of the Expectation Effect

The theoretical results obtained in the previous sections provide key insight into why the expectation effect exists and how it can be asymmetric across regimes. But how important quantitatively is the expectation effect of regime shifts? How does the expectation effect affect equilibrium dynamics when monetary policy shifts from the dovish regime to the hawkish regime? We address these issues using the model presented in Section III.2. This kind of model has been a workhorse for quantitative monetary analysis.[5] Specifically, we allow for different sources of frictions and

[5]See, for example, Galí and Gertler (1999), Chari, Kehoe, and McGrattan (2000), Ireland (2004), Lubik and Schorfheide (2004), CEE (2005), Boivin and Giannoni (2006), Del Negro, et al. (2007), and Smets and Wouters (2007).

shocks. This generalization makes closed-form solution impossible to obtain. We solve the model (27)-(29) numerically and obtain our results through simulations under the parameterization discussed next.[6]

IV.1. **Parameterization.** The parameters in our regime-switching model include both constant and regime-dependent parameters. The constant parameters include β, the subjective discount factor; b, the habit parameter; ξ, the inverse Frisch elasticity of labor supply; α, the elasticity of output with respect to labor; θ, the elasticity of substitution between differentiated goods; η, the Calvo probability that a firm cannot re-optimize its pricing decision; ι, the degree of inflation indexation; μ and ρ_μ, the mean and the AR(1) coefficient of the markup shock process; λ, the trend growth rate of productivity; ρ_a and ρ_ν, the AR(1) coefficients of the preference shock and of the productivity growth processes; and σ_r, σ_a, σ_μ, and σ_ν, the standard deviations of the monetary policy shock, the preference shock, the markup shock, and the technology shock. The regime-dependent parameters include policy parameters ρ_r, ϕ_π, and ϕ_y.

The baseline values of the parameters for our simulations are summarized in Table 1. These parameter values correspond to a quarterly model. We set $\lambda = 1.005$ so that the average annual growth rate of per capital GDP is 2%. We set $\beta = 0.9952$ so that, given the value of λ, the average annual real interest rate (equal to λ/β) is 4%. Following the literature, we set $b = 0.75$, which is in the range considered by Boldrin, Christiano, and Fisher (2001). The parameter ξ corresponds to the inverse Frisch elasticity of labor supply, which is small (Pencavel, 1986) according to most micro-studies. We set $\xi = 2$, corresponding to a Frisch elasticity of 0.5. We set $\alpha = 0.7$, corresponding to a labor income share of 70%. The substitution-elasticity parameter θ determines the steady-state markup and is set at 10, in line with the values used by Basu and Fernald (2002) and Rotemberg and Woodford (1997).

The Calvo parameter η is set at 0.66, which lies within the range of the empirical estimates (Taylor (1999), CEE (2005), and Eichenbaum and Fisher (2007)). Following Christiano, Eichenbaum, and Evans (2005), we set $\iota = 1$ as the baseline value. For the parameters governing the shock processes, we set $\rho_a = 0.9$, $\rho_\nu = 0.2$, $\rho_\mu = 0.9$, $\sigma_a = 0.2$, $\sigma_r = 0.2$, $\sigma_\mu = 0.2$, and $\sigma_\nu = 0.2$. To isolate the effect of regime shifts in

[6]Unlike the standard linear Taylor rule, regime-dependent coefficients in the policy rule make the equilibrium dynamics non-linear, and the solution method becomes non-standard. We use the solution method developed by Farmer, Waggoner, and Zha (2006) to solve our Markov-switching rational expectations model. The specific steps that we take in solving the model are described in Appendices C and D.

monetary policy, we control for the shock variances to be constant across regimes. It is important to note that our conclusions about expectation effects hold for a wide range of values of these parameters.

To focus our attention on the policy responses to inflation, we set $\rho_r = 0.55$ and $\phi_y = 0.5$ in both regimes.[7] In our baseline exercise, we consider two considerably different policies, represented by $\phi_{\pi,1} = 0.9$ in the dovish regime and $\phi_{\pi,2} = 2.5$ in the hawkish regime. All these values are in line with the estimate obtained by Clarida, Galí, and Gertler (2000) and Lubik and Schorfheide (2004).

For the parameters in the transition matrix Q, we set $q_{11} = 0.95$ and $q_{22} = 0.95$ (and accordingly, $q_{21} = 0.05$ and $q_{12} = 0.05$). These parameter values imply that both regimes are very persistent on the quarterly frequency. In our quantitative analysis, we experiment with other values of transition probabilities to ensure the robustness of our results.

IV.2. **Asymmetric expectation effects.** To gauge the importance of the expectation effect of a shift in policy regime, we compare the dynamic behavior of macroeconomic variables in our regime-switching model with that in the version of the model in which agents naively assume that the current regime would prevail indefinitely.

Figure 1 displays the impulse responses of inflation, output, the ex ante real interest rate, expected inflation, expected output, and the real marginal cost under the dovish regime. At the top of the graphs, "Policy" stands for a monetary policy shock, "Demand" for a preference shock, "Markup" for a markup shock, and "Tech" for a technology shock. Within each graph, two sets of impulse responses are plotted. One corresponds to the version of the model where agents naively assume that the current regime will last indefinitely (the solid line), and the other corresponds to the baseline version of our model where agents take regime switching into account in forming their expectations (the dashed line). The difference between these two sets of impulse responses represents the expectation effect of regime switching in policy. As shown in Figure 1, the dynamic responses of all variables (particularly those following the demand shock or the cost-push shock) are substantially dampened. The expectation of regime switching to the hawkish regime, even if agents expect the policy to shift from the dovish regime to the hawkish regime with a modest probability of only 5%, help anchor agents' inflation expectations. This effect will be amplified if we allow the dovish regime to be less persistent so that it is more likely to switch to the hawkish regime.

[7]Our results hold even if ρ_r is set to zero.

Figure 2 displays the impulse responses in the hawkish regime. Since the expectation of regime switching to the dovish regime does not affect the responses much, hawkish monetary policy effectively anchors agents' inflation expectations. This finding is consistent with the view that U.S. monetary policy since mid-1980s has been effective in stabilizing inflation despite the belief that this hawkish policy may not last forever (Bernanke and Mishkin, 1997; Mishkin, 2004; Goodfriend and King, 2005).

To measure the quantitative importance of the expectation effect and the magnitude of its asymmetry across regimes, we compute the volatilities of inflation, output, and the nominal interest rate. The volatilities are derived from the solution to our structural model, which takes the following reduced form

$$x_t = G_{1,s_t} x_{t-1} + G_{2,s_t} \epsilon_t, \tag{38}$$

where matrices G_{1,s_t} and G_{2,s_t} are functions of the structural parameters. To derive the unconditional volatility of x_t for regime j ($j = 1, 2$), we fix $G_{1,s_t} = G_{1,j}$ and $G_{2,s_t} = G_{2,j}$ for all t in (38) and compute $\Omega_j^{\text{tot}} = E x_t x_t'$ as

$$\text{vec}(\Omega_j^{\text{tot}}) = (I - G_{1,j} \otimes G_{1,j})^{-1} \, \text{vec}(G_{2,j} G_{2,j}'). \tag{39}$$

The unconditional volatility of x_t in regime j is measured by the square root of the diagonal of Ω_j^{tot}. The first three variables of x_t are inflation, output, and the nominal interest rate, and their volatilities thus computed are reported in Table 2.

The strong expectation effect in the dovish regime and the lack of it in the hawkish regime are evident by comparing the results across Panels A and B in Table 2. In the dovish regime, the expectation of a shift to the hawkish regime lowers macroeconomic volatility, especially inflation volatility. The table shows that, when the expectation effect is taken into account, the unconditional volatility of inflation is lowered by about 60% (from 0.67 to 0.27) and that of the nominal interest rate is lowered by about 54% (from 0.65 to 0.30). The output volatility is also reduced, although to a lesser extent (about a 25% reduction). In comparison, in the hawkish regime, the expectation of a shift to the dovish regime has a much smaller effect on macroeconomic volatility: the volatilities of inflation, output, and the nominal interest rate are raised only by 19.3%, 2.8%, and 3.9%, respectively.[8]

[8]The small expectation effect of regime switches in the hawkish regime holds even when the regime is much less persistent (e.g., when $q_{22} = 0.7$). On the other hand, the expectation effect in the dovish regime remains very strong even if we set $q_{11} = 0.98$ and $q_{22} = 1.0$, the probabilities that might fit into some researchers' a priori belief. The result of asymmetric expectation effects is also robust to allowing the Calvo probability η and the inflation indexation parameter ι, not strictly "deep" parameters, to

IV.3. **Endogenous Propagation.** Endogenous propagation mechanisms in our model play an important role in generating the asymmetric expectation effects of regime switches both in level and proportionally. A weaker propagation mechanism gives rise to less persistent dynamics of inflation and output and therefor smaller and less asymmetric expectation effects.

To see this point, we turn off the endogenous propagation mechanisms by setting $b = \iota = 0$ and $\alpha = 1$. To obtain closed form solutions, we further set $\rho_r = \phi_y = 0$. It follows from Propositions 6 and 9 that the expectation effect, although asymmetric in level, is *proportionally* symmetric across regimes.[9] More formally, we have

$$\frac{\bar{v}_{\pi,1} - v_{\pi,1}}{\bar{v}_{\pi,1}} = \frac{v_{\pi,2} - \bar{v}_{\pi,2}}{\bar{v}_{\pi,2}}.$$

In contrast, as we show in Section IV.2, a strong propagation mechanism in the model with habit formation, dynamic indexation, and firm-specific factors gives rise to more persistence in the dynamics of inflation and output and thus stronger asymmetric expectation effects.

IV.4. **Equilibrium Determinacy.** In our baseline parameterization, $\phi_{\pi,1} < 1$ violates the Taylor principle, implying local equilibrium indeterminacy if the dovish regime were to last indefinitely. As argued previously, the expectation effect arises not because one of the regimes leads to indeterminacy; it exists as long as the two policy regimes differ in their aggressiveness against inflation fluctuations.

To make this point concrete, we set $\phi_{\pi 1} = 1.01$ (instead of 0.9 used in the baseline parameterization), while keeping all other parameters the same. With this variation, the interest rate satisfies the Taylor principle and the equilibrium is unique in both regimes. Table 3 reports the volatility results. It is evident that although indeterminacy does not arise here, the expectation effect of regime switching remains quantitatively important under the dovish regime (especially for inflation and the nominal interest rate), but is much less important under the hawkish regime.

V. Conclusion

We have studied two canonical DSGE models with monetary policy following a Markov-switching process between a dovish regime and a hawkish regime, where monetary policy in the hawkish regime responds to inflation more strongly than in the

vary with regime changes in policy (see Liu, Waggoner, and Zha (2007), an earlier version of the paper).

[9]The same conclusion holds for the flexible-price model presented in Section III.1.

dovish regime. We have shown, in theory and through simulations, that (1) because inflation expectations can be influenced, in a nonlinear way, either by the hawkish policy itself or through the expectation of switching to this policy, the expectation effect is asymmetric across regimes; (2) in the dovish regime, the expectation effect can be quantitatively important, a theoretical result consistent with the evidence that changes in policy regime may not be the main source of the substantial volatility reduction observed in macroeconomic time series; and (3) in the hawkish regime, on the other hand, the expectation effect of a change in future policy is quantitatively less important. The asymmetry of expectation effects across the two policy regimes offers one plausible explanation of why the post-1982 monetary policy in the United States has been successful in reducing the volatility of both inflation and output, despite agents' disbelief that the hawkish policy will prevail indefinitely (Goodfriend and King, 2005).

Our finding that the expectation effect can be quantitatively important provides a clear argument for continuing the existing line of research on Markov-switching DSGE models that explicitly incorporates the possibility of regime shifts in agent's information set. A more ambitious task is to estimate a regime-switching DSGE model with a long data sample that covers different policy regimes. Some progress has been made in this direction (Liu, Waggoner, and Zha, 2008). We believe that this line of research can be both important and fruitful.

TABLE 1. Constant parameters

Preference	$\beta = 0.9952$	$\xi = 2$	$b = 0.75$	
Technology	$\alpha = 0.7$	$\lambda = 1.005$	$\theta = 10$	
Price setting	$\eta = 0.66$	$\iota = 1$		
Policy rule	$\rho_r = 0.55$	$\phi_y = 0.5$		
Aggregate Shocks				
Persistence	$\rho_a = 0.9$	$\rho_\mu = 0.9$	$\rho_\nu = 0.2$	
Standard dev.	$\sigma_r = 0.2$	$\sigma_a = 0.2$	$\sigma_\mu = 0.2$	$\sigma_\nu = 0.2$
Regime transition prob.	$q_{11} = 0.95$	$q_{22} = 0.95$		

TABLE 2. Effects of regime shifts on macroeconomic volatility (baseline: $\phi_{\pi,1} = 0.9$ and $\phi_{\pi,2} = 2.5$)

	A. *Ignoring Expectation Effects*		
Regime	Inflation	Output	Interest rate
Dovish	0.669	0.277	0.648
Hawkish	0.057	0.177	0.205
	B. *Accounting for Expectation Effects*		
Regime	Inflation	Output	Interest rate
Dovish	0.268	0.209	0.301
Hawkish	0.068	0.182	0.213

TABLE 3. Effects of regime shifts on macroeconomic volatility (determinacy: $\phi_{\pi,1} = 1.01$ and $\phi_{\pi,2} = 2.5$)

	A. *Ignoring Expectation Effects*		
Regime	Inflation	Output	Interest rate
Dovish	0.302	0.212	0.345
Hawkish	0.057	0.177	0.205
	B. *Accounting for Expectation Effects*		
Regime	Inflation	Output	Interest rate
Dovish	0.196	0.200	0.261
Hawkish	0.065	0.180	0.211

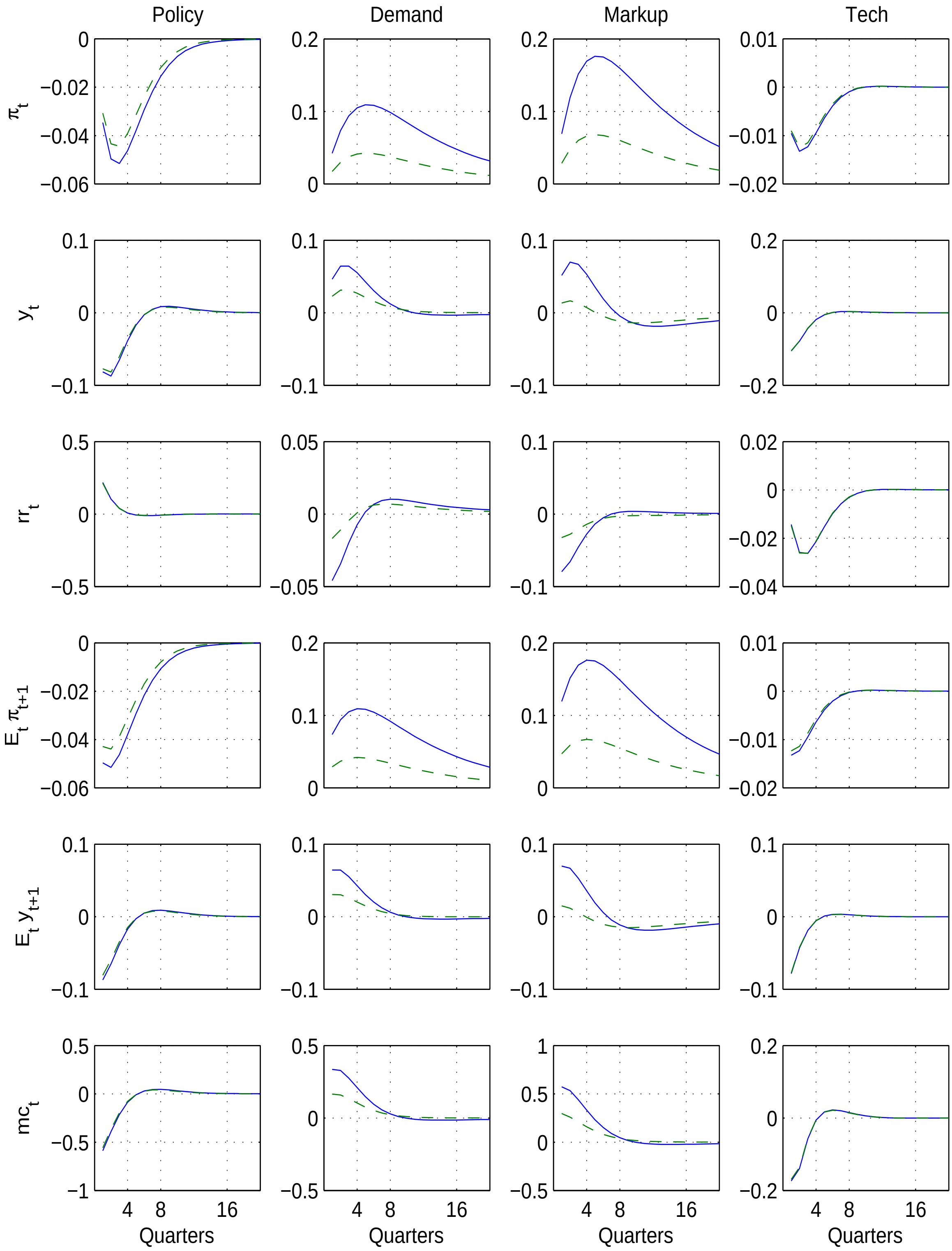

FIGURE 1. Impulse responses under the dovish policy regime. The solid line represents the responses from the model that ignores regime shifts in future policy. The dashed line represents the responses from our regime-switching model.

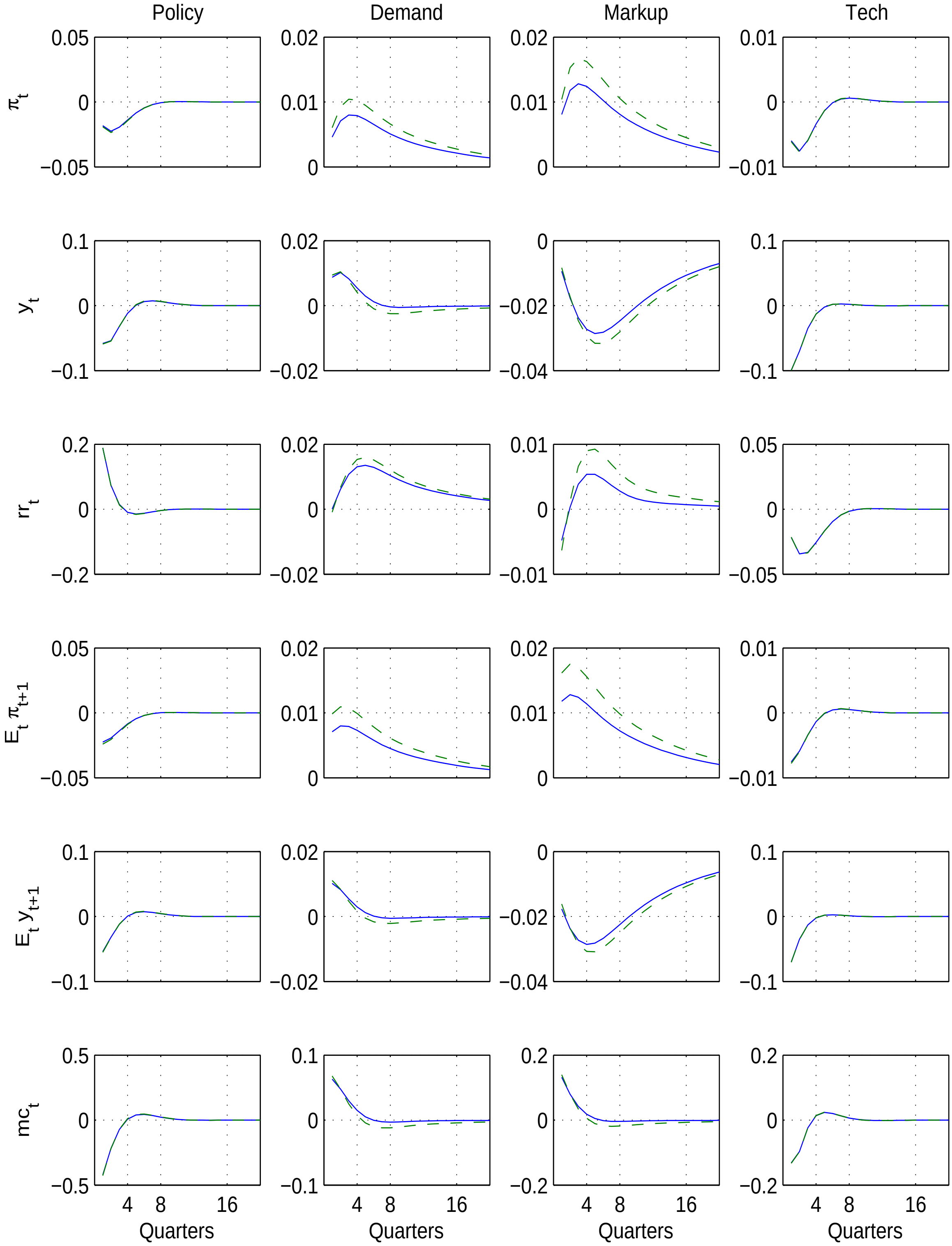

FIGURE 2. Impulse responses under the hawkish policy regime. The solid line represents the responses from the model that ignores regime shifts in future policy. The dashed line represents the responses from our regime-switching model.

Appendix A. Stationary Equilibrium and Steady State in the DSGE Model

We derive the stationary equilibrium and steady state in the DSGE model described in Section III.2. We begin with the individuals' optimizing conditions.

The representative household takes prices as given and chooses consumption C_t, labor hours L_t, and bond holdings B_{t+1} to maximize the utility (14) subject to the budget constraint (15). The optimizing decisions imply the labor supply equation

$$\frac{W_t}{\bar{P}_t} = \Psi(C_t - bC_{t-1})L_t^{\xi} \tag{A1}$$

and the intertemporal Euler equation

$$1 = \beta \mathrm{E}_t \frac{A_{t+1}}{A_t} \frac{C_t - bC_{t-1}}{C_{t+1} - bC_t} \frac{\bar{P}_t}{\bar{P}_{t+1}} R_t. \tag{A2}$$

If firm $j \in [0,1]$ can re-optimize its pricing decision, it chooses the price $P_t(j)$ to maximize the profit (24), taking the demand schedule (18) as given. The optimal pricing rule is given by

$$\mathrm{E}_t \sum_{i=0}^{\infty} \eta^i D_{t,t+i} Y_{t+i}^d(j) \frac{1}{\mu_{t+i} - 1} \left[\mu_{t+i}\Phi_{t+i}(j) - P_t(j)\chi_{t,t+i}\right] = 0, \tag{A3}$$

where $\Phi_{t+i}(j)$ denotes the marginal cost given by

$$\Phi_{t+i}(j) = \frac{1}{\alpha} \frac{W_{t+i}}{Z_{t+i}} \left(\frac{Y_{t+i}(j)^d}{Z_{t+i}}\right)^{1/\alpha - 1}. \tag{A4}$$

Because the productivity shock Z_t in the model contains a trend, we focus on a stationary equilibrium (i.e., the balanced growth path). We make appropriate transformations of the relevant variables to induce stationarity. The variables to be transformed include aggregate output, consumption, and the real wage. In equilibrium, all these variables grow at the same rate as does the productivity, so we divide each of these variables by Z_t and denote the resulting stationary counterpart of the variable X_t by $\tilde{X}_t = X_t/Z_t$.

We now describe the steady-state equilibrium, where all shocks are turned off. The steady-state equilibrium can be summarized by the solution to the four equilibrium conditions: the optimal pricing decision (A3), the labor supply equation (A1), the intertemporal Euler equation (A2), and the Taylor rule (26).

The optimal pricing equation (A3) implies that, in the steady state, the real marginal cost is equal to the inverse of the markup:

$$\frac{1}{\mu_p} = \frac{1}{\alpha} \tilde{W} \tilde{Y}^{1/\alpha - 1}, \tag{A5}$$

where $\tilde{W} = \frac{W}{PZ}$ denotes the transformed real wage and $\tilde{Y} = \frac{Y}{Z}$ denotes transformed output.

The labor supply equation (A1) implies that the real wage in the steady state equals the marginal rate of substitution (MRS):

$$\tilde{W} = \Psi L^{\xi} \left(\tilde{Y} - \frac{b}{\lambda} \tilde{Y} \right), \tag{A6}$$

where we have used the market clearing condition that aggregate consumption equals aggregate output in equilibrium.

The household's optimal intertemporal decision (A2) implies that, in the steady-state equilibrium, we have

$$\frac{R}{\pi} = \frac{\lambda}{\beta}. \tag{A7}$$

The Taylor rule in the steady-state equilibrium implies that

$$R = \kappa(s)^{1/(1-\rho_r(s))} \left(\frac{\pi}{\pi^*} \right)^{\phi_\pi(s)} \tilde{Y}^{\phi_y(s)}. \tag{A8}$$

In the steady-state equilibrium, there is a classical dichotomy. The real variables $\tilde{Y}$ and $\tilde{W}$ are determined by the first two equations (A5)–(A6), while the nominal variables π and R are determined by the other two equations (A7)–(A8) once the real variables are determined.

Although the monetary policy rule can switch regime, the steady state does not depend on the policy regime. To see this, we set $\kappa(s) = \left[\frac{\lambda}{\beta} \pi^* \tilde{Y}^{-\phi_y(s)} \right]^{1-\rho(s)}$ where $\tilde{Y}$ can be solved from the "real part" of the equilibrium system (i.e.,(A5)–(A6). With $\kappa(s)$ so chosen, we obtain the unique steady-state value for inflation and the nominal interest rate:

$$\pi = \pi^*, \quad R = \frac{\lambda}{\beta} \pi^*. \tag{A9}$$

Appendix B. Proofs of Propositions

B.1. **Proof of Proposition 1.** We solve the model (8) by the method of undetermined coefficients. Given the solution form $\hat{\pi}_t = \alpha_{s_t} \hat{a}_t$ for $s_t \in \{1, 2\}$, (8) implies that

$$\begin{aligned} \phi_1 \alpha_1 \hat{a}_t &= q_{11} \alpha_1 \rho_a \hat{a}_t + q_{21} \alpha_2 \rho_a \hat{a}_t + \gamma(1-\rho_a)\hat{a}_t, \\ \phi_2 \alpha_2 \hat{a}_t &= q_{12} \alpha_1 \rho_a \hat{a}_t + q_{22} \alpha_2 \rho_a \hat{a}_t + \gamma(1-\rho_a)\hat{a}_t, \end{aligned}$$

where we have used the relation $\mathrm{E}_t\hat{a}_{t+1} = \rho_a\hat{a}_t$. Matching the coefficients on $\hat{a}_t$, we obtain

$$\phi_1\alpha_1 = q_{11}\alpha_1\rho_a + q_{21}\alpha_2\rho_a + \gamma(1-\rho_a), \tag{A10}$$

$$\phi_2\alpha_2 = q_{12}\alpha_1\rho_a + q_{22}\alpha_2\rho_a + \gamma(1-\rho_a). \tag{A11}$$

It follows that the solution $[\alpha_1, \alpha_2]'$ is given by the expression in (9).

B.2. **Proof of Proposition 2.** Denote by $\alpha = [\alpha_1, \alpha_2]'$ and $C = \gamma(1-\rho_a)[1,1]'$. The MSV solution in (9) can be rewritten as

$$\alpha = A^{-1}C.$$

Since A is positive definite, α_1 and α_2 are both positive.

To establish the first inequality in (10), we impose the relation $q_{11} = 1 - q_{21}$ and differentiate (A10) and (A11) with respect to q_{21} to obtain

$$\begin{aligned}\phi_1\frac{\partial\alpha_1}{\partial q_{21}} &= q_{11}\rho_a\frac{\partial\alpha_1}{\partial q_{21}} + (\alpha_2-\alpha_1)\rho_a + q_{21}\rho_a\frac{\partial\alpha_2}{\partial q_{21}}\\ \phi_2\frac{\partial\alpha_2}{\partial q_{21}} &= q_{12}\rho_a\frac{\partial\alpha_1}{\partial q_{21}} + q_{22}\rho_a\frac{\partial\alpha_2}{\partial q_{21}}.\end{aligned}$$

With appropriate substitutions, we get

$$\frac{\partial\alpha_1}{\partial q_{21}} = \frac{\gamma(1-\rho_a)^2(\phi_2 - q_{22}\rho_a)(\phi_1-\phi_2)}{\det(A)^2} < 0,$$

where the inequality follows from the assumption that $\phi_1 < 1 < \phi_2$. Similarly, we can show that

$$\frac{\partial\alpha_2}{\partial q_{12}} = \frac{\gamma(1-\rho_a)^2(\phi_1 - q_{11}\rho_a)(\phi_2-\phi_1)}{\det(A)^2}.$$

Since A is assumed to be positive definite, we have $\det(A) > 0$ so that

$$\phi_1 - q_{11}\rho_a > \frac{q_{21}q_{12}\rho_a^2}{\phi_2 - q_{22}\rho_a} > 0.$$

This inequality, along with the assumption that $\phi_2 > \phi_1$, implies that $\frac{\partial\alpha_2}{\partial q_{12}} > 0$.

B.3. **Proof of Proposition 3.** Given the solution form $\hat{\pi}_t = \bar{\alpha}_j\hat{a}_t$, we have $\mathrm{E}_t\hat{\pi}_{t+1} = \bar{\alpha}_j\rho_a\hat{a}_t$ and (12) is a result from matching the coefficients of $\hat{a}_t$.

B.4. **Proof of Proposition 4.** The solution for the regime-switching model (9) can be rewritten as

$$\alpha_j = \frac{q_{ij}\rho_a + \phi_i - q_{ii}\rho_a}{\det(A)}, \quad i\, j \in \{1, 2\}, \quad i \neq j.$$

Using the solution for the constant regime model in (12), we have

$$\begin{aligned}
\frac{\bar{\alpha}_1 - \alpha_1}{\alpha_2 - \bar{\alpha}_2} &= \frac{\frac{1}{\phi_1 - \rho_a} - \frac{q_{21}\rho_a + \phi_2 - q_{22}\rho_a}{\det(A)}}{\frac{q_{12}\rho_a + \phi_1 - q_{11}\rho_a}{\det(A)} - \frac{1}{\phi_2 - \rho_a}} \\
&= \frac{\phi_2 - \rho_a}{\phi_1 - \rho_a} \frac{\det(A) - (\phi_1 - \rho_a)(q_{21}\rho_a + \phi_2 - q_{22}\rho_a)}{(\phi_2 - \rho_a)(q_{12}\rho_a + \phi_1 - q_{11}\rho_a) - \det(A)} \\
&= \frac{\phi_2 - \rho_a}{\phi_1 - \rho_a} \frac{1 - q_{11}}{1 - q_{22}}.
\end{aligned}$$

The desired inequality in (13) follows from the assumptions that $q_{11} = q_{22}$ and $\phi_2 > \phi_1$.

B.5. **Proof of Proposition 5.** We solve the model (33) by using the method of undetermined coefficients. The conjectured solution implies that

$$\begin{aligned}
\beta\rho_a^2[\gamma_1(q_{11}^2 + q_{21}q_{12}) + \gamma_2 q_{21}(q_{11} + q_{22})] - \rho_a(1 + \beta + \kappa)(\gamma_1 q_{11} + \gamma_2 q_{21}) + (1 + \kappa\phi_1)\gamma_1 &= \kappa(1 - \rho_a) \\
\beta\rho_a^2[\gamma_2(q_{22}^2 + q_{21}q_{12}) + \gamma_1 q_{12}(q_{11} + q_{22})] - \rho_a(1 + \beta + \kappa)(\gamma_2 q_{22} + \gamma_1 q_{12}) + (1 + \kappa\phi_2)\gamma_2 &= \kappa(1 - \rho_a),
\end{aligned}$$

where we have used the Markov transition property of the regime switching process and the AR(1) property of the shock and we have also matched the coefficients for $\hat{a}_t$ in each equation. Collecting terms, we obtain the solution (34).

B.6. **Proof of Proposition 7.** The MSV solution (34) can be written in a compact form $A\gamma = B$, where $\gamma = [\gamma_1, \gamma_2]'$ and $B = [1, 1]'\kappa(1 - \rho_a)$. Total differentiation with respect to q_{21}, we obtain

$$\frac{\partial A}{\partial q_{21}}\gamma + A\frac{\partial \gamma}{\partial q_{21}} = 0,$$

where

$$\begin{aligned}
\frac{\partial A}{\partial q_{21}}\gamma &= (\gamma_2 - \gamma_1)\begin{bmatrix} \rho_a[\beta\rho_a(2q_{11} + q_{22} - 1) - (1 + \beta + \kappa)] \\ \beta\rho_a^2 q_{12} \end{bmatrix} \\
&= \frac{\kappa^2(1 - \rho_a)(\phi_1 - \phi_2)}{det(A)}\begin{bmatrix} \rho_a[\beta\rho_a(2q_{11} + q_{22} - 1) - (1 + \beta + \kappa)] \\ \beta\rho_a^2 q_{12} \end{bmatrix}.
\end{aligned}$$

With some further algebra, we obtain

$$\frac{\partial \gamma_1}{\partial q_{21}} = \frac{\kappa^2(1 - \rho_a)(\phi_2 - \phi_1)}{det(A)^2}\left\{-(\beta\rho_a^2)^2(1 - q_{11})^2(1 - q_{22}) + \right.$$
$$\left. [\beta(\rho_a q_{22})^2 - (1 + \beta + \kappa)\rho_a q_{22} + 1 + \kappa\phi_2][\beta\rho_a^2(q_{11} + q_{22} - q_{21}) - \rho_a(1 + \beta + \kappa)]\right\} < 0.$$

where the last inequality follows since $\phi_2 > \phi_1$ and, given that $\phi_2 > 1$, the term in the first square bracket is positive (while the term in the second square bracket is clearly negative).

Following similar steps, we obtain

$$\frac{\partial \gamma_2}{\partial q_{12}} = \frac{\kappa^2(1-\rho_a)(\phi_1-\phi_2)}{det(A)^2}\left\{-(\beta\rho_a^2)^2(1-q_{22})^2(1-q_{11})+ \right.$$
$$\left. [\beta(\rho_a q_{11})^2-(1+\beta+\kappa)\rho_a q_{11}+1+\kappa\phi_1][\beta\rho_a^2(q_{11}+q_{22}-q_{12})-\rho_a(1+\beta+\kappa)]\right\}.$$

Since $\phi_1 < \phi_2$ and the term in the last square bracket is negative, to show that $\frac{\partial \gamma_2}{\partial q_{12}} > 0$, it is sufficient to establish that $\beta(\rho_a q_{11})^2 - (1+\beta+\kappa)\rho_a q_{11} + 1 + \kappa\phi_1 > 0$. The desired inequality follows from the assumption in Proposition 6 that $\kappa(\phi_1 - \rho_a) > -(1-\rho_a)(1-\beta\rho_a)$ (so that $\bar{\gamma}_1 > 0$).

Appendix C. Solving the Regime-Switching Structural Model

Our model features Markov switching monetary policy regime and the rational expectations equilibrium is in general non-linear. Thus, the standard methods for solving rational expectations models such as those described by Blanchard and Kahn (1980), King and Watson (1998), and Uhlig (1999) do not apply. To solve our Markov-switching rational expectations model, we use the generalized minimum state variable (MSV) approach developed by Farmer, Waggoner, and Zha (2006), which utilizes the canonical VAR form of Sims (2002).

We use the following notation:

- n = number of all variables (including expectation terms) for each regime, as in the Gensys setup
- m = number of fundamental shocks
- $\tilde{h}$ = number of policy regimes
- h^* = number of shock regimes
- n_1 = number of equations in each regime
- n_2 = number of expectation errors
- n_3 = number of fixed-point equations
- $\tilde{Q} = \tilde{h} \times \tilde{h}$ matrix of transition matrix, whose elements sum up to 1 in each column

In our model, we have $n = 8$, $m = 4$, $\tilde{h} = 2$, $h^* = 1$, $n_1 = 6$, $n_2 = 2$, $n_3 = n_2(\tilde{h}-1) = 6$.

We can now rewrite the equilibrium conditions described in (27) - (29) and the shock processes (1), (22), and (17) in the compact form

$$\underset{n_1\times n}{A_{s_t}}\underset{n\times 1}{x_t} = \underset{n_1\times n}{B_{s_t}}\underset{n\times 1}{x_{t-1}} + \underset{n_1\times m}{\Psi}\underset{m\times 1}{\varepsilon_t}, \tag{A12}$$

where

$$x_t = [\hat{\pi}_t, \tilde{y}_t, \hat{R}_t, \hat{a}_t, \hat{\mu}_t, \hat{\nu}_t, \mathrm{E}_t\hat{\pi}_{t+1}, \mathrm{E}_t\tilde{y}_{t+1}]'$$

is a 8×1 vector of variables to be solved and

$$\varepsilon_t = [\varepsilon_{rt}, \varepsilon_{at}, \varepsilon_{wt}, \varepsilon_{\nu t}]'$$

is a 4×1 vector of shocks.

The coefficient matrices A_{s_t} and B_{s_t} in (A12) involve parameters that are possibly regime-dependent. We now fill in the matrices A_{s_t}, B_{s_t}, and Ψ using the three equilibrium conditions and three shock processes as follows.

$$\underset{6\times 8}{A_{s_t}} =$$
$$\begin{bmatrix} -[1+\beta\gamma] & \psi\left[\frac{1+\xi}{\alpha}+\frac{b}{\lambda-b}\right] & 0 & 0 & \psi & \frac{\psi b}{\lambda-b} & \beta & 0 \\ 0 & -\frac{\lambda+b}{\lambda} & -\frac{\lambda-b}{\lambda} & \frac{(\lambda-b)(1-\rho_a)}{\lambda} & 0 & \frac{\rho_\nu\lambda-b}{\lambda} & \frac{\lambda-b}{\lambda} & 1 \\ -(1-\rho(s_t))\phi_\pi(s_t) & -(1-\rho(s_t))\phi_y(s_t) & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix},$$

$$\underset{6\times 8}{B_{s_t}} = \begin{bmatrix} -\gamma & \psi\frac{b}{\lambda-b} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{b}{\lambda} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho(s_t) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \rho_a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \rho_w & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \rho_\nu & 0 & 0 \end{bmatrix},$$

$$\underset{6\times 4}{\Psi} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \sigma_r & 0 & 0 & 0 \\ 0 & \sigma_a & 0 & 0 \\ 0 & 0 & \sigma_w & 0 \\ 0 & 0 & 0 & \sigma_\nu \end{bmatrix},$$

Following Farmer, Waggoner, and Zha (2006), we can expand the system under each regime, described above, into an expanded linear system to obtain the MSV solution. Appendix D describes the detail of how to form this expanded system.

Appendix D. The Expanded Model

To solve the model described in (A12), we stack all variables under each regime and form an expanded model

$$\underset{16\times 16}{A}\ \underset{16\times 1}{X_t} = \underset{16\times 16}{B}\ \underset{16\times 1}{X_{t-1}} + \underset{16\times 24}{\Gamma_u}\ \underset{24\times 1}{u_t} + \underset{16\times 2}{\Gamma_\eta}\ \underset{2\times 1}{\eta_t}, \tag{A13}$$

where

$$\underset{16\times 1}{X_t} = \begin{bmatrix} \underset{8\times 1}{x_{1,t}} \\ \underset{8\times 1}{x_{2,t}} \end{bmatrix} \equiv \begin{bmatrix} \boldsymbol{\iota}\{s_t = 1\}\ \underset{8\times 1}{x_t} \\ \boldsymbol{\iota}\{s_t = 2\}\ \underset{8\times 1}{x_t} \end{bmatrix},$$

$$\underset{16\times 16}{A} = \begin{bmatrix} \underbrace{\text{diag}(A_1, \ldots, A_h)}_{12\times 16} \\ \underbrace{2 \text{ expectation errors}}_{2\times 16} \\ \underbrace{2 \text{ fixed} - \text{point equations}}_{2\times 16} \end{bmatrix},$$

$$= \begin{bmatrix} \underbrace{\text{diag}(A_1, A_2)}_{12\times 16} \\ \underbrace{\begin{bmatrix} \boldsymbol{I}_2 & \boldsymbol{O}_{2\times 6} & \vdots & \boldsymbol{I}_2 & \boldsymbol{O}_{2\times 6} \end{bmatrix}}_{2\times 16} \\ \underbrace{\begin{bmatrix} \boldsymbol{O}_{2\times 8} & \Phi(s=2)_{2\times 8} \end{bmatrix}}_{2\times 16} \end{bmatrix}$$

$$\underset{16\times 16}{B} = \begin{bmatrix} \underbrace{\text{diag}(B_1, B_2)(\tilde{Q} \otimes \boldsymbol{I}_8)}_{12\times 16} \\ \underbrace{2 \text{ expectation errors}}_{2\times 16} \\ \underbrace{\boldsymbol{O}_{2\times 16}}_{2\times 16} \end{bmatrix}$$

$$= \begin{bmatrix} \underbrace{\begin{bmatrix} q_{11}B_1 & q_{12}B_1 \\ q_{21}B_2 & q_{22}B_2 \end{bmatrix}}_{12\times 16} \\ \underbrace{\begin{bmatrix} \boldsymbol{O}_{2\times 6} & \boldsymbol{I}_2 & \boldsymbol{O}_{2\times 6} & \boldsymbol{I}_2 \end{bmatrix}}_{2\times 16} \\ \underbrace{\boldsymbol{O}_{2\times 16}}_{2\times 16} \end{bmatrix},$$

$$\underset{16\times 24}{\Gamma_u} = \left[\begin{array}{c:c} \boldsymbol{I}_{12} & \boldsymbol{I}_{12} \\ \boldsymbol{O}_{4\times 12} & \boldsymbol{O}_{4\times 12} \end{array}\right], \quad \underset{24\times 1}{u_t} = \left[\begin{array}{c} \underset{12\times 16}{S_{s_t}} \ \underset{16\times 1}{X_{t-1}} \\ \hdashline \underset{12\times 1}{\mathcal{E}_t} \end{array}\right],$$

$$\begin{aligned} \underset{12\times 16}{S_{s_t}} &= \begin{bmatrix} (\boldsymbol{\iota}\{s_t = 1\} - \tilde{q}_{11})\, B_1 & (\boldsymbol{\iota}\{s_t = 1\} - \tilde{q}_{12})\, B_1 \\ (\boldsymbol{\iota}\{s_t = 2\} - \tilde{q}_{21})\, B_2 & (\boldsymbol{\iota}\{s_t = 2\} - \tilde{q}_{22})\, B_2 \end{bmatrix} \\ &\equiv \operatorname{diag}(B_1, B_2)[(\boldsymbol{e}_{s_t}\mathbf{1}_2' - \tilde{Q}) \otimes \boldsymbol{I}_8], \end{aligned}$$

$$\boldsymbol{e}_{s_t} = \begin{bmatrix} \boldsymbol{\iota}\{s_t = 1\} \\ \boldsymbol{\iota}\{s_t = 2\} \end{bmatrix}, \ \mathbf{1}_2 = \begin{bmatrix} 1 \\ 1 \end{bmatrix},$$

$$\underset{24\times 1}{\mathcal{E}_t} = \underbrace{\begin{bmatrix} \Psi & \boldsymbol{O} \\ \boldsymbol{O} & \Psi \end{bmatrix}}_{12\times 16} \underbrace{\begin{bmatrix} \boldsymbol{\iota}\{s_t = 1\}\varepsilon_t \\ \boldsymbol{\iota}\{s_t = 2\}\varepsilon_t \end{bmatrix}}_{16\times 1},$$

$$\underset{16\times 2}{\Gamma_\eta} = \begin{bmatrix} \boldsymbol{O}_{12\times 2} \\ \boldsymbol{I}_2 \\ \boldsymbol{O}_{2\times 2} \end{bmatrix}.$$

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