Nonlinear DSGE model with Asymmetric Adjustment Costs under ZLB: Bayesian Estimation with Particle Filter for Japan *

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Abstract

From the viewpoint of Bayesian approach with particle filter, we estimate the latest Japanese economy between 1985Q3 and 2015Q1 including more than one decade zero interest rate policy, using a nonlinear New Keynesian DSGE models extending asymmetric adjustment costs (AAC) to Rotemberg price setting mechanism and zero lower bound (ZLB) to monetary policy rule. Model selection in terms of marginal likelihood shows that the both ZLB and AAC overwhelmingly contribute to explain fluctuations of his output growth, inflation and nominal interest rate. This result indicates that the adjustment costs in rising prices are about 33-48% higher than ones in dropping prices, and that the policy function of inflation is mostly likely to be shaped as strong convex, because the ZLB amplifies deflation and the AAC inhibits rising price level. The wide curved policy functions make the effects of monetary policy shock much more uncertain expressing as spread credible bands of the impulse responses, whereas variations of estimated structural shocks are rarely influenced in spite of adding both assumptions. We also report models with only the ZLB constraint mislead the effect of monetary policy to output and inflation over-estimated when we estimate Japan.

Keywords, New Keynesian model, zero lower bound, Rotemberg price setting, policy function iterations, projection method, particle filter Metropolis-Hastings algorithm

JEL Classifications, C11, C32, C52

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*The views expressed herein are of our own and do not represent those of the organizations the authors belongs to.

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1 Introduction

Motivation

- We apply a nonlinear New Keynesian (NK) DSGE extended to two aspects to Japanese economy for the last thirty years including so called "Bubble boom" and "Lost decade" by using advance techniques for solving and estimating models.
- What difference between nonlinear and linear DSGE models when estimating Japan.

Related Literature

- What difference between nonlinear and linear NK DSGE models under zero lower bound (ZLB) were studied by Fernandez-Villaverde et al. (2015).
- Richter et al. (2014) concluded that a time iteration method with linear interpolation (TL) has got the best balance between speed and precision for solving nonlinear DSGE models under ZLB within the class of policy function iteration.
- Recently, a textbook dealing with Bayesian estimation for DSGE including nonlinear model has been published by Herbst and Schorfheide (2016).
- Gust et al. (2013) estimated a nonlinear New Keynesian (NK) DSGE under ZLB for US, using particle filter Metropolis-Hastings (PFMH) algorithm .
- Aruoba et al (2014) and Aruoba and Schorfhide (2015) estimated a New Keynesian DSGE under ZLB with regime switching of target inflation for Japan as well as US and EU.

What we do

- Instead of considering regime switching of target inflation, we focus on asymmetry adjustment costs with respect to the target inflation (or steady state of inflation). And we combine TL method for solving a nonlinear model provided by Richter et al. (2014) and PFMH explained by Herbst and Schorfheide (2016), and extend the NK model estimated by Gust et al. (2013) to adding aymmetric adjustment costs in order to estimate deflation for the last three decades in Japan, between 1985:Q3 and 2015:Q1.
- Model selection in terms of marginal likelihood shows that the both assumptions overwhelmingly contribute to explain fluctuations of his output growth, inflation and nominal interest rate. This result indicates that the adjustment costs in rising prices are about 33-48% higher than ones in dropping prices, and that the policy function of inflation is mostly likely to be shaped as strong convex, because the ZLB amplifies deflation and the AAC inhibits rising price level.

- The wide curved policy functions make the effects of monetary policy shock much more uncertain expressing as spread credible bands of the impulse responses, whereas variations of estimated structural shocks are rarely influenced in spite of adding both assumptions.
- We also report only the ZLB constraint misleads the effect of monetary policy to output growth and inflation over-estimated when we estimate Japan.

2 Model

We embed the following two assumptions in a small-scale New Keynesian DSGE model that studied by An and Schorfheide (2007) and Herbst and Schorfheide (2016)[1], and numerically solve a rational expectations equilibrium (REE) directly from a non-linear original model but not a log-linearized version studied by the previous researches.

2.1 Monetary Policy under ZLB

Monetary policy rule is constrained by ZLB and written as [2]

$$R_t = \max(\, 1,\ R_t^{*1-\rho_R} R_{t-1}^{\rho_R} e^{\epsilon_{R,t}}\ ), \tag{1}$$

where R_t is the gross nominal interest rate, R_t^* is nominal target rate and $\epsilon_{R,t}$ is monetary policy shock. The nominal target rate, R_t^*, is given as[3]

$$R_t^* = r\pi^* \left(\frac{\pi_t}{\pi^*}\right)^{\psi_1} \left(\frac{Y_t}{Y_t^*}\right)^{\psi_2}, \tag{2}$$

where π^* and Y_t^* is inflation target (or steady state of inflation) and output target, respectively.

2.2 Asymmetric Adjustment Cost (AAC)

Adjustment costs (AC) adopted by Rotemberg[4] are etented to variant costs with asymmetrically state-dependent on inflation, π_t, as below.

$$AC_t(j) = \frac{\phi(\pi_t)}{2}\left(\frac{P_t(j)}{P_{t-1}(j)} - \pi^*\right)^2 Y_t(j), \tag{3}$$

$$\phi(\pi_t) = \begin{cases} \phi_1(= (1+\delta)\phi_2 > \phi_2), & \text{if } \frac{P_t(j)}{P_{t-1}(j)}\ (=\pi_t)\ \geq\ \pi^* \\ \phi_2, & \text{if } \frac{P_t(j)}{P_{t-1}(j)}\ (=\pi_t)\ <\ \pi^* \end{cases},$$

[1]Aruba et al (2014) and Aruoba and Schorfhide (2015) also used the model and extent it to regime switching model under ZLB.

[2]We exten Eq. (1.10) of Herbst and Schorfheide (2016) to monetary policy rule under ZLB.

[3]Eq.(2) is corresponding to Eq. (1.11) of Herbst and Schorfheide (2016).

[4]We exten Eq. (1.6) of Herbst and Schorfheide (2016) toAsymmetric adjustment costs.

where $\phi(\pi_t)$ is coefficient of the AC and δ is fraction of the cost generated when rising prices against when decline of prices. Although asymmetric adjustment costs (AAC) were studied by Kim and Ruge-Murcia (2009), our setting is easy and intuitive to show that the costs kink around the steady state of inflation, π^*, and that the costs when rising price of goods are higher than when dropping the prices.

2.3 Agencys

Firms

Monopolistically competitive intermediate goods producing firms maximize the present value of future profits: Π, [5] under the following two conditions.

$$\prod = E_t \left[\sum_{s=0}^{\infty} \beta^s Q_{t+s|t} \left(\frac{P_{t+s}(j)}{P_t} Y_{t+s}(j) - W_{t+s} N_{t+s}(j) - AC_{t+s}(j) \right) \right],$$

where β is discount factor. The one condition is the demand for intermediate goods, j, given by[6]

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-1/\nu} Y_t,$$

where ν is inverse elasticity of demand for goods j. And the other is the linear production technology as [7]

$$Y_t(j) = A_t N_t(j),$$

where A_t and $N_t(j)$ are exogenous common productivity process and the labor input of firm j, respectively.

Households

The households maximize utilities, U , under the budget constraint[8]

$$U = E_t \left[\sum_{s=0}^{\infty} \beta^s \left(\frac{(C_{t+s}/A_{t+s})^{1-\tau} - 1}{1-\tau} + \chi_M \ln \left(\frac{M_{t+s}}{P_{t+s}} \right) - \chi_H H_{t+s} \right) \right],$$

where τ is inverse elasticity of intertemporal substitution of consumption. And the household's budget constraint is [9]

$$P_t C_t + B_t + M_t + T_t = P_t W_t H_t + R_{t-1} B_{t-1} + M_{t-1} + P_t D_t + P_t SC_t,$$

[5]This equation is corresponding to Eq. (1.7) of Herbst and Schorfheide (2016).
[6]This equation is corresponding to Eq. (1.3) of Herbst and Schorfheide (2016).
[7]This equation is corresponding to Eq. (1.5) of Herbst and Schorfheide (2016).
[8]This equation is corresponding to Eq. (1.8) of Herbst and Schorfheide (2016).
[9]This equation is corresponding to Eq. (1.9) of Herbst and Schorfheide (2016).

Government

The government's budget is given by constraint[10]

$$P_tG_t + R_{t-1}B_{t-1} + M_{t-1} = T_t + B_t + M_t,$$

and the government's expenditure is described by

$$G_t = \left(1 - \frac{1}{g_t}\right) Y_t. \tag{4}$$

2.4 Exogenous Shocks

Aggregate productivity evolves as nonstationary process as below.[11]

$$\ln A_t = \ln \gamma + \ln A_{t-1} + \ln z_t, \;\; \ln z_t = \rho_z \ln z_{t-1} + \epsilon_{z,t}, \tag{5}$$

where γ stands for average technology growth rate, z_t is the exogenous fluctuation of the technology growth rate and $\epsilon_{z,t}$ is the productivity shock. The fraction of government to aggregate ouput is given by [12]

$$\ln g_t = (1 - \rho_g) \ln g + \rho_g \ln g_{t-1} + \epsilon_{g,t}, \tag{6}$$

where $\epsilon_{g,t}$ is government shock. This shock could be regarded as a aggregate exogenous demand shock.

2.5 Equilibrium Relationships

The potential aggregate output (or target level of output in the monetary policy rule)[13]

$$Y_t^* = (1 - \nu)^{1/\tau} A_t g_t, \tag{7}$$

The market clearing conditions are given by [14]

$$Y_t = C_t + G_t + AC_t, \;\; N_t = H_t, \tag{8}$$

The optimality conditions of households (or the consumption Euler equation): [15]

$$1 = \beta E_t \left[\left(\frac{C_{t+1}/A_{t+1}}{C_t/A_t} \right)^{-\tau} \frac{A_t}{A_{t+1}} \frac{R_t}{\pi_{t+1}} \right] \tag{9}$$

And the optimality conditions of intermediate firms:[16]

[10]This equation is corresponding to Eq. (1.12) of Herbst and Schorfheide (2016).
[11]This equation is corresponding to Eq. (1.13) of Herbst and Schorfheide (2016).
[12]This equation is corresponding to Eq. (1.14) of Herbst and Schorfheide (2016).
[13]This equation is corresponding to Eq. (1.19) of Herbst and Schorfheide (2016).
[14]This equation is corresponding to Eq. (1.15) of Herbst and Schorfheide (2016).
[15]This equation is corresponding to Eq. (1.17) of Herbst and Schorfheide (2016).
[16]This equation is corresponding to Eq. (1.18) of Herbst and Schorfheide (2016).

$$
\begin{aligned}
1 &= \phi(\pi_t)\ (\pi_t - \pi) \left[\left(1 - \frac{1}{2\nu}\right) \pi_t + \frac{\pi}{\pi_{t+1}} \right] \\
&- \phi(\, E_t(\pi_{t+1})\,)\ \beta E_t \left[\left(\frac{C_{t+1}/A_{t+1}}{C_t/A_t} \right)^{-\tau} \frac{Y_{t+1}/A_{t+1}}{Y_t/A_t} (\pi_{t+1} - \pi)\pi_{t+1} \right] \\
&+ \frac{1}{\nu} \left[1 - \left(\frac{C_t}{A_t} \right)^{\tau} \right].
\end{aligned} \tag{10}
$$

Notice that due to asymmetric adjustment costs the sizes of $\phi(\pi_t)$ and $\phi(E_t(\pi_{t+1})\,)$ in the first and the second terms of the RHS depend on the values of current inflation, π_t, and expected inflation, $E_t(\pi_{t+1})$, respectively.

2.6 Variations of our Models

To solve our nonlinear models, we use above ten equations (1) through (10) corresponding to ten endogenous variables: Y_t, Y_t^*, C_t, G_t, AC_t, π_t, R_t, R_t^*, A_t, g_t , and three exogenous structural shocks: $\varepsilon_{R,t}$, $\varepsilon_{z,t}$, $\varepsilon_{g,t}$. And there are 15 parameters such as β, τ, ν, ϕ_2, δ, ψ_1, ψ_2, γ, π^*, ρ_r, ρ_g, ρ_z, σ_r, σ_g, σ_z, all of which are estimated. The definitions of the parameters are summarized in Table 1.

We examine and estimate four models classified with respect to the two assumptions. The four models are summarized in Table 2.

- Model 1: in absence of the ZLB and the AAC
- Model 2: in presence of the ZLB
- Model 3: in presence of the AAC
- Model 4: in presence of both the ZLB and the AAC

Here, we incorporate the standard monetary policy rule, $R_t = R_t^{*1-\rho_R} R_{t-1}^{\rho_R} e^{\epsilon_{R,t}}$, into the models in absence of the ZLB binds, instead of Eq.(1). In the models in absence of the AAC, we use a invariant coefficient, ϕ , in Eq.(3), instead of $\phi(\pi_t)$.

[Insert Table 1 and Table 2]

3 Solution and Estimation Methods

3.1 Projection Method

The model is solved using a *time iteration method with linear interpolation* (TL) within the class of projection methods (or policy function iteration methods). Richtcher et al. (2014) reported TL provides the best balance between speed and accuracy. In addition, TL outperforms time iteration with Chebyshev polynominal, which is the popular method in the class of policy function iteration, when the ZLB constraint is embeded.

The model's decision rules (or policy functions) can be written as

$$(\ Y_t/A_t, \ \pi_t, \ R_t \ ) = \mathcal{P}(\ R_{t-1}, \ g_t, \ z_t \, \varepsilon_{R,t} \ ), \tag{11}$$

where Y_t/A_t, π_t, and R_t in the LHS are control variables in the decision rules and R_{t-1}, g_t, z_t, and $\varepsilon_{R,t}$ in the RHS are state variables of the function. We specify nine grid points on each continurous state variables which implies 729 nodes. The Appendix shows our solving method.

3.2 PFMH

We estimate the nonlinear model using Bayesian methods with particle filter, following Gust et al. (2012) . Particle filter Metropolis-Hastings algorithm (PFMH), or Particle Markov Chain Monte Carlo (PMCMC), was established in Andrieu et al. (2010). We describe the algorithm in the Appendix following Herbst and Schorfheide (2016, ch 8 and ch 9). After solving for the decision rule, $\mathcal{P}(\ R_{t-1}, \ g_t, \ z_t, \ \varepsilon_{R,t} \ )$, our economic environment can be represented as nonlinear state space model consisting of the following two equations (12) and (13).

State Equations

The policy functions, Eq.(11), are used as a state equation for estimation by combined with Eq. (1), (5) and (6), and rewritten as

$$s_t = \Phi(s_{t-1}, \varepsilon_t, \theta), \tag{12}$$

where s_t is endogenous variables: $s_t = (\, Y_t/A_t, \ \pi_t, \ R_t, \ g_t, \ z_t \,)$, and $\varepsilon_t = (\ \varepsilon_{R,t}, \ \varepsilon_{g,t}, \ \varepsilon_{z,t} \ )$. θ is the parametars.

Measurement Equations

A measurement equation represents connection between endogenous variables and observed variables as

$$y_t = \psi(s_t, \theta) + u_t,$$

where y_t is observed variables and u_t is measurement errors. We set the measurement equation as Eq. (13).

$$\begin{bmatrix} YGR_t(\%) \\ INFL_t(\%) \\ INT_t(\%) \end{bmatrix} = \begin{bmatrix} 100/4 \times (\ln (Y_t/A_t) - \ln (Y_{t-1}/A_{t-1}) + \ln z_t + \ln \gamma) \\ 100 \times \ln \pi_t \\ 100 \times \ln R_t \end{bmatrix} + \begin{bmatrix} u_{y,t} \\ u_{\pi,t} \\ u_{r,t} \end{bmatrix}. \tag{13}$$

where three observations in the LHS are adopted for estimation: quarter-to-quarter real GDP growth rate (YGR), annualized quarter-to-quarter inflation rates (INFL), and annualized nominal interest rates (INT). These three series are measured in percentage.

3.3 Data and Prior Setting

Data and Sample Period

We estimate the model using Japan data on output growth (Δy_t), inflation (π_t), and nominal interest rate rates (R_t) from 1985:Q3 through 2015:Q1. Following Aruoba et al. (2014), we collect real GDP figures from the Cabinet Office's National Accounts. We used the statistical release of benchmark year 2005 that cover the period 1994Q1-2015Q1. To extend the sample, we collected them from the benchmark year 2000 release and spanned the period 1985Q3-2015Q1. For the price level we use the implicit GDP deflator index from the Cabinet Office. We also extend the benchmark year 2005 release using the growth rate of the index from the benchmark year 2000 release in the same way as real GDP. For the nominal interest rate we use the Bank of Japan's uncollateralized call rate and transformed monthly figures to quarterly averages over the sample period.

Prior setting

Table 1 shows the prior disributions of the structural parameters. These distributions are assumed to be independent across parameters.

4 Empirical Results

4.1 Posterior Estimations and Model Selection

Table 2 shows log marginal likelihoods and posterior model probabilities of the four models. And Table 3 shows posterior means and 90% credible intervals of 15 parameters of the models. As Table 2, Models 3 and 4 holding the assumption of the AAC have much higher the likelihood than Models 1 and 2 without the AAC, so that the AAC must be the necessary assumption to explain deflations during the last three decades in Japan. In addition, since posterior model probability of Model 4 is as much as 97.7%, the model including the ZLB and the AAC is thought to be very close to the true model among the four models. On the other hand, that the likelihood of Model 2 is lower than the reference model, Model 1, indicates that the model holding only the ZLB constraint seems to fail to estimate Japanese economy overall for both of interest rate policy period and conventional monetary policy period.

The parameter δ of Model 3 and 4 in Table 3 have around 0.46 and 0.33 as posterior means, respectively. This result indicates that the adjustment costs in rising prices are likely to be about 33% through 46% higher than ones in dropping prices, and that it is much hard for producing firms to rise the prices of their goods rather than to decline the prices.

[Insert Table 3]

4.2 Estimated Policy Functions

Using posterior means of the parameters in the four models, their policy functions are calculated and shown at Figure 1. Graphs in the first, second and third rows are the functions in term of the three state variables: z_t, R_{t-1} and g_t, respectively. Generally, reactions of the functions in Model 4 (red bold line) are drawn between Model 1 (green line) and Model 2 (blue line), and that suggests that addition of the AAC mitigates reactions to output and inflation. More detail focusing on the graphs, reaction of the technology growth rate z_t to inflation in Model 4 (red line) seems to be shaped as stronger convex than Model 2 (blue line), whereas reaction of Model 1 is obviously linear as shown at the top line and the second column. As the figure at the third column, reactions to interest rate in the two models with the ZLB are kinked at over unity of z_t. On the other hand, there are no big difference in impacts of government shocks g_t on the three endogenous variables among the four models as the third row. These results also suggest that if Model 4 is close to true as the marginal likelihood shows, the model with only ZLB bind as Model 2 might overestimate responses of the TFP and monetary shocks to output and inflation.

[Insert Fig. 1]

4.3 Nonlinear Filtering of Variables and Shocks

Figures 2 through 4 show posterior estimations of output, inflation and interest rate derived from particle filter, respectively. The black solid line, blue shaded area and red dashed line stand for the posterior means, the 68% credible intervals and the observed series, respectively. As Figure 2, 68% range of output becomes much tighter by incorporations of the AAC, the ZLB or both, since these assumptions could contribute to explain the flactuation. Meanwhile, estimated inflation and output of Model 2 through 4 show that it is difficult to explain synchronization of deep deflation and boom in output happened between 2002 and 2005 in terms of the AAC and the ZLB, as the black lines do not almost match the corresponding red lines. To explain this period we need to extend our model from another aspect. We remain this discrepancy as this puzzle to solve in the next research.

Figure 5 shows posterior means of estimated exogenous three shocks of the four models. Surprisingly, there are no big differences among these estimated shocks, even though the two assumptions are added. This suggests that we can robustly estimate movements of structural shocks no matter what extension are conducted in a model.

[Insert Fig. 2 through Fig.5]

4.4 Estimated Impulse Response

Figure 6 shows means (blue line) and 95% interval (light blue shaded area) of impulse response functions (IRF) of monetary policy shock in the four models calculated with posterior means of the parameters by using generalized impulse response method (Koop et al. ,1996). As panel (b) and (c), the 95% (or 2 times standard deviation of simulations) bands are very wide by introducing the ZLB, since policy functions of Models 2 and 4 in Figure 1 are deeply curved. Under the ZLB, the effect of monetary policy depends not only on the size of the shocks but also on the situation of state variables. It suggests forecasting of effects of monetary policy are the most uncertain around zero interest rate. The IRF of Model 3 has slightly wide range so that the AAC makes policy functions curved, whereas the IRF of Model 1 has narrow one and their policy functions are flat. Finaly, we report that the impulse responses on inflation and output in the models with only the ZLB bind are much bigger than other three as panel (b) and it suggests that only the ZLB constraint misleads the effect of monetary policy overestimated in the case of the latest Japanese economy.

[Insert Fig. 6]

5 Conclusion

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A Appendix

A.1 Projection Method

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A.2 PFMH

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B Tables

Table 1: Prior Setting

parameters	definition	distribution	parameter 1	parameter 2
β	discount factor	beta	0.98	0.01
τ	inverse elasticity of substitution	gamma	2.0	0.1
ν	inverse elasticity of demand for goods	gamma	0.3	0.1
ϕ_2	coef. of adjustment costs	gamma	20.0	10.0
δ	Degree of asymmetric AC	beta	0.25	0.1
ψ_1	reaction of inflation	normal	1.5	0.5
ψ_2	reaction of output	normal	0.5	0.5
γ	average technology growth rate	normal	1.04	0.01
π	Steady state inflation rate	normal	1.0	0.01
ρ_r	persistence of MP shock	beta	0.75	0.1
ρ_g	persistence of Gov shock	beta	0.75	0.1
ρ_z	persistence of TFP shock	beta	0.75	0.1
σ_r	St.D. of MP iid shock	Inverse gamma	0.5	5
σ_g	St.D. of Gov iid shock	Inverse gamma	0.5	5
σ_z	St.D. of TFP iid shock	Inverse gamma	0.5	5

Notes: In Beta and Normal distributions, parameter 1 and 2 represent mean and Standard deviation, respectively.

Table 2: Model Definitions and Model Selection

	ZLB	AAC	Log Marginal Likelihood	Posterior Model Prob
Model 1	No	No	-765.154	0.000
Model 2	Yes	No	-769.307	0.000
Model 3	No	Yes	-757.336	0.023
Model 4	Yes	Yes	-753.582	0.977

Notes: ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

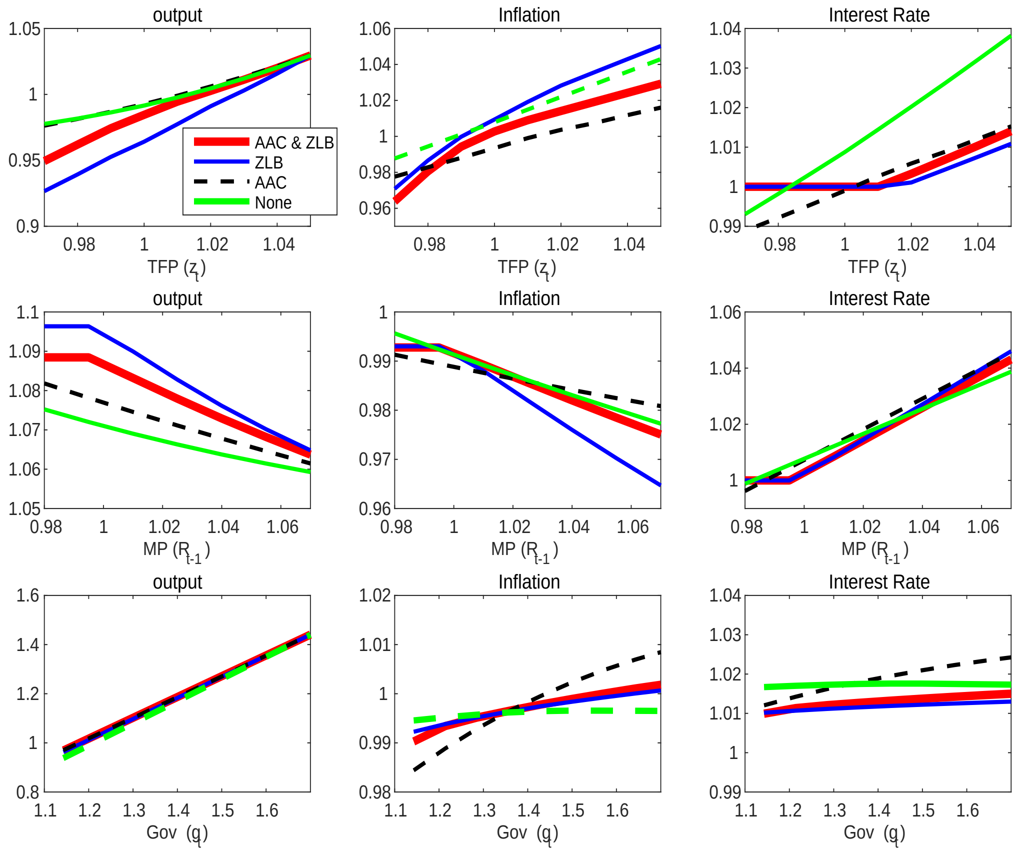
Table 3: Posterior Parameters Estimations

parameters	Model 1	Model 2 ZLB	Model 3 AAC	Model 4 ZLB & AAC
β	0.98 [0.98, 0.98]	0.98 [0.98, 0.98]	0.98 [0.98 0.98]	0.98 [0.98, 0.98]
τ	2.62 [2.60, 2.63]	2.99 [2.98, 3.00]	3.12 [3.11, 3.14]	2.86 [2.84, 2.87]
ν	0.21 [0.21, 0.23]	0.38 [0.37, 0.38]	0.42 [0.42, 0.43]	0.37 [0.35, 0.38]
ϕ_2	14.97 [14.41, 15.77]	15.78 [15.34, 16.14]	17.40 [17.02, 17.91]	15.59 [15.18, 15.96]
δ	N.A.	N.A	0.46 [0.42, 0.50]	0.33 [0.27, 0.44]
ψ_1	1.72 [1.71, 1.73]	1.57 [1.55, 1.58]	1.34 [1.33, 1.35]	1.71 [1.70, 1.72]
ψ_2	0.44 [0.43 0.45]	0.42 [0.41, 0.43]	0.39 [0.38, 0.40]	0.62 [0.61, 0.63]
γ	1.01 [1.01, 1.01]	1.01 [1.00, 1.01]	1.02 [1.02, 1.02]	1.01 [1.01, 1.01]
π	1.00 [1.00, 1.00]	1.00 [1.00, 1.00]	1.00 [1.00, 1.00]	1.00 [1.00, 1.00]
ρ_r	0.61 [0.61 0.62]	0.80 [0.80, 0.81]	0.64 [0.63, 0.65]	0.74 [0.73, 0.75]
ρ_g	0.93 [0.93 0.94]	0.87 [0.87, 0.88]	0.92 [0.91, 0.93]	0.91 [0.91, 0.92]
ρ_z	0.76 [0.75, 0.77]	0.83 [0.83, 0.84]	0.80 [0.80, 0.81]	0.82 [0.82, 0.83]
σ_r	0.29 [0.29, 0.29]	0.25 [0.25, 0.25]	0.32 [0.32, 0.32]	0.32 [0.32 0.33]
σ_g	0.63 [0.63, 0.63]	0.69 [0.69, 0.69]	0.28 [0.28, 0.29]	0.37 [0.37 0.37]
σ_z	0.43 [0.43, 0.43]	0.31 [0.31, 0.32]	0.53 [0.53, 0.54]	0.34 [0.34, 0.34]

Notes: In the first row in each parameter, the value represents their posterior mean. In the second row, the values within parenthesis stand for 90% credible bands. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

C Figures

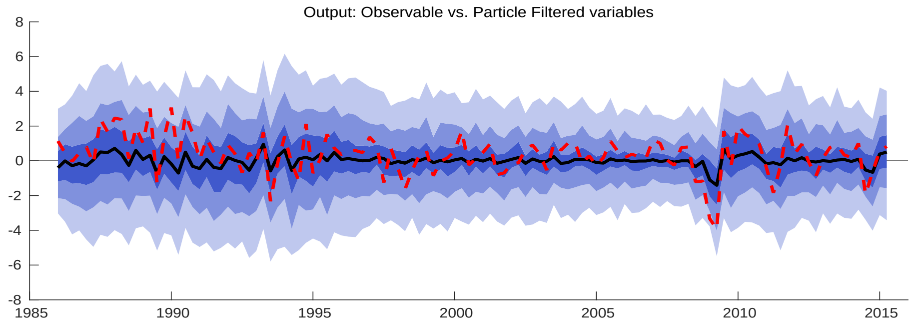
Figure 1: Posterior Estimation of Policy Functions



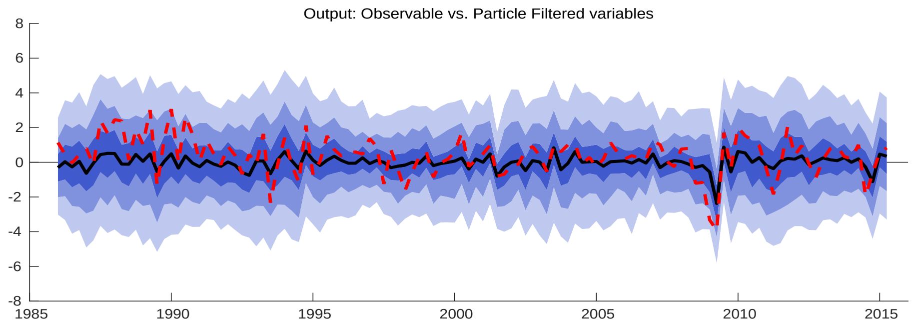
Notes: The above policy functions are calculated from posterior means of parameters. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

Figure 2: Posterior Estimates of Real GDP

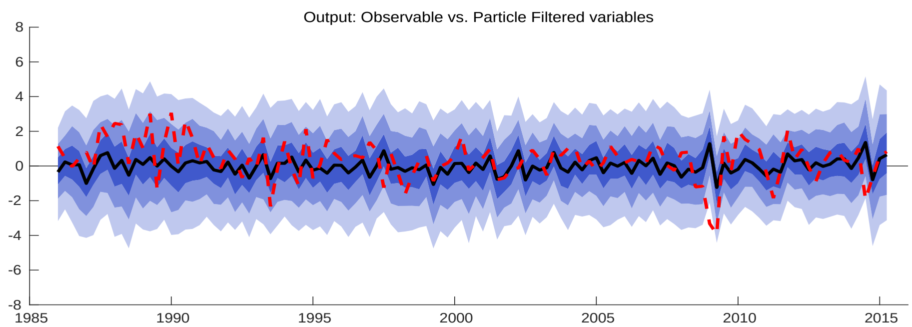
(a) Model 1 (w/o both AAC and ZLB)



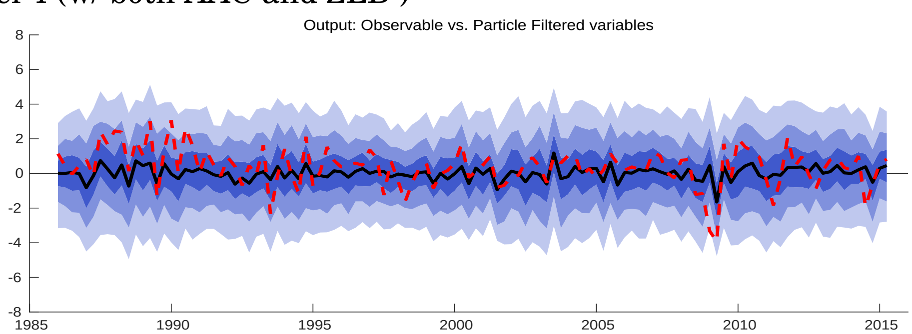
(b) Model 2 (w/o AAC and w/ ZLB)



(c) Model 3 (w/ AAC and w/o ZLB)



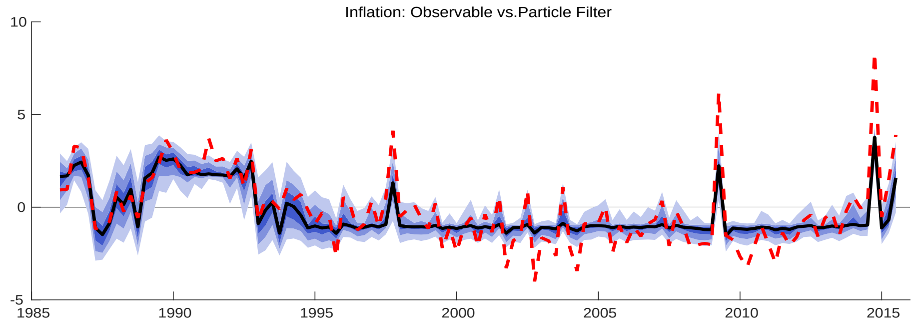
(d) Model 4 (w/ both AAC and ZLB)



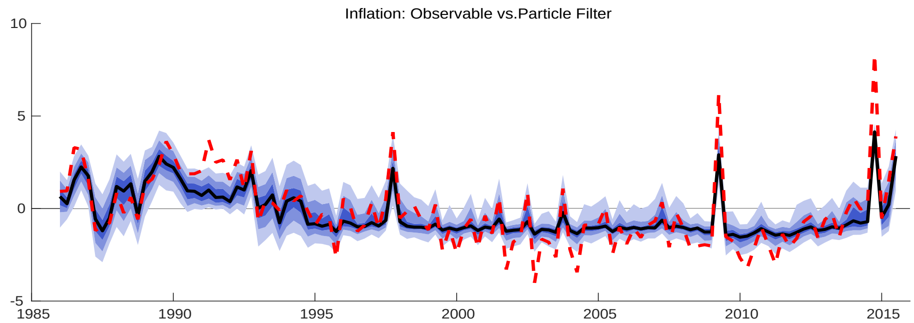
Notes: The black solid line and the red dashed line stand for posterior mean and actual data, respectively. The blue shaded areas represent 68% credible band. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

Figure 3: Posterior Estimates of Inflation

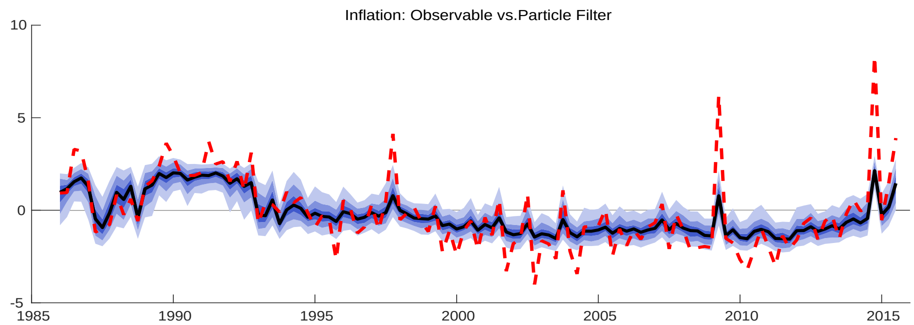
(a) Model 1 (w/o both AAC and ZLB)



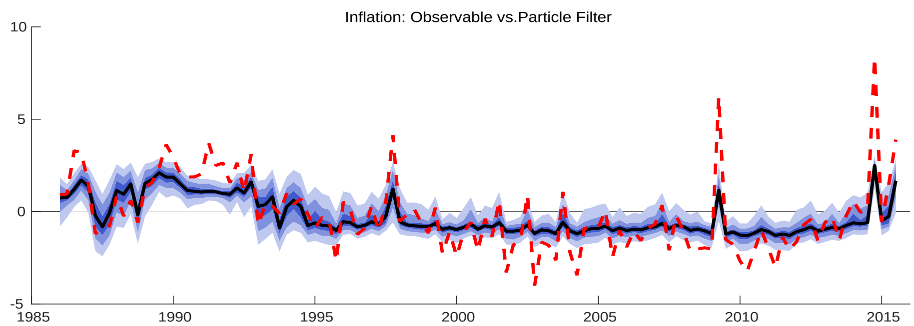
(b) Model 2 (w/o AAC and w/ ZLB)



(c) Model 3 (w/ AAC and w/o ZLB)



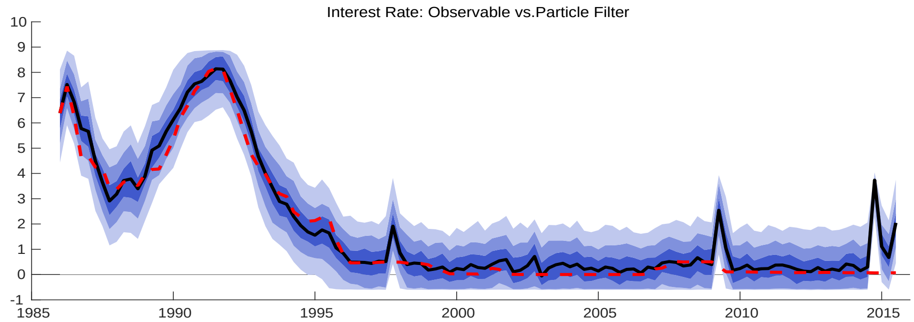
(d) Model 4 (w/ both AAC and ZLB)



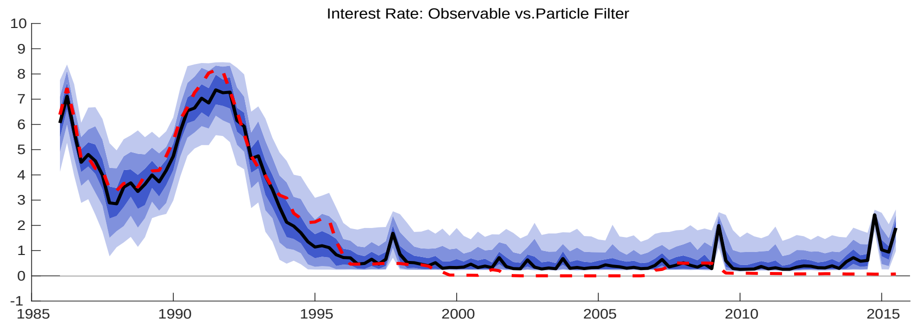
Notes: The black solid line and the red dashed line stand for posterior mean and actual data, respectively. The blue shaded areas represent 68% credible band. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

Figure 4: Posterior Estimates of Interest Rate

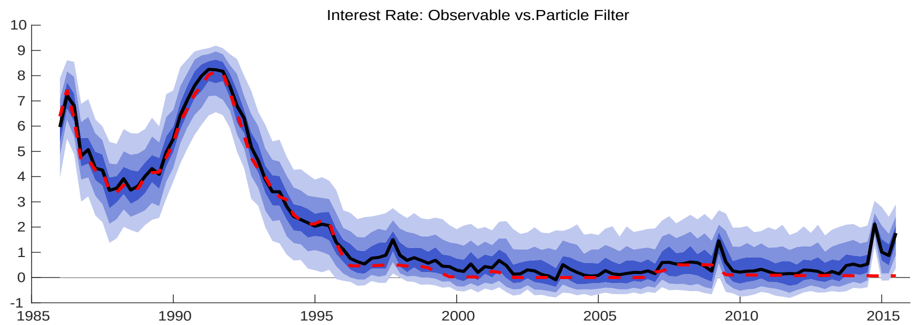
(a) Model 1 (w/o both AAC and ZLB)



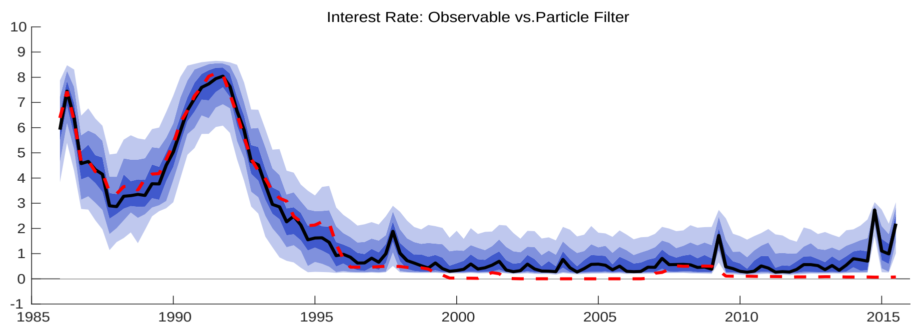
(b) Model 2 (w/o AAC and w/ ZLB)



(c) Model 3 (w/ AAC and w/o ZLB)

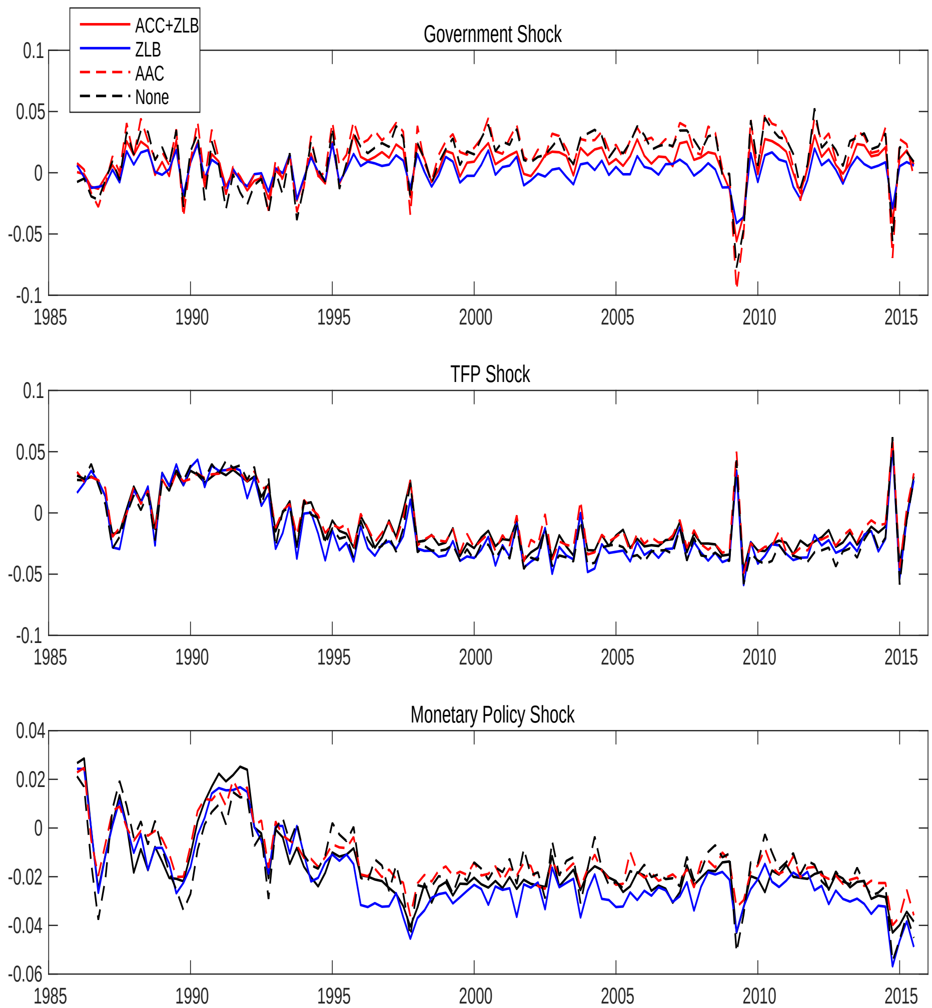


(d) Model 4 (w/ both AAC and ZLB)



Notes: The black solid line and the red dashed line stand for posterior mean and actual data, respectively. The blue shaded areas represent 68% credible band. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

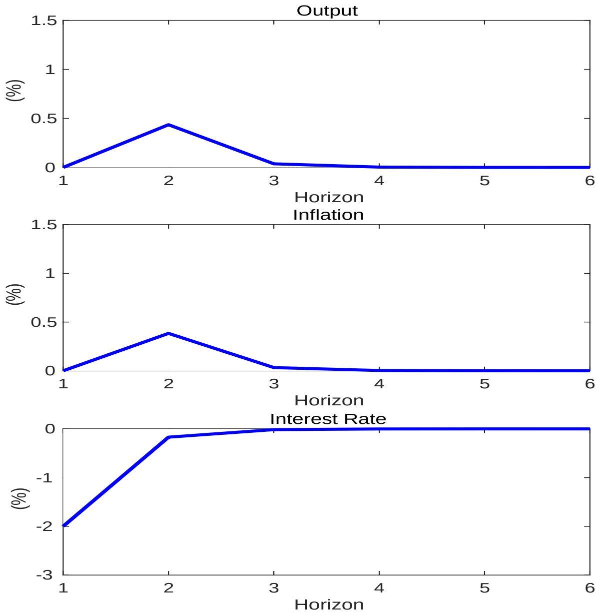
Figure 5: Posterior Estimates of Exogenous shocks



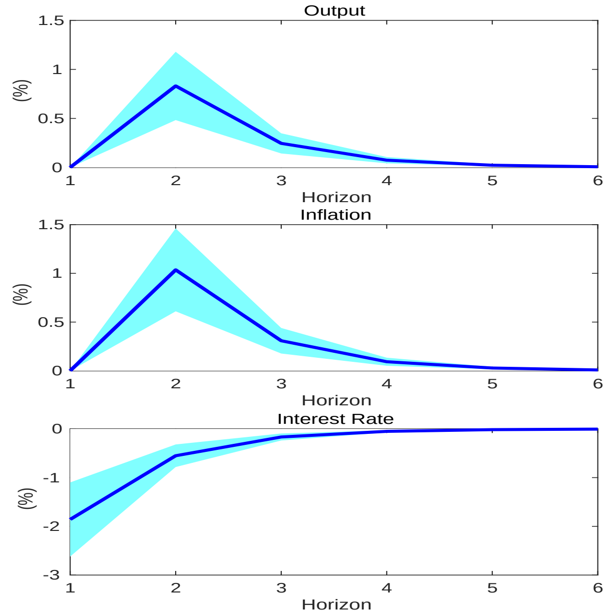
Notes: Posterior Estimates of shocks are posterior means derived from samples acumulated. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.

Figure 6: Impulse Response Functions of Monetary Policy Shock

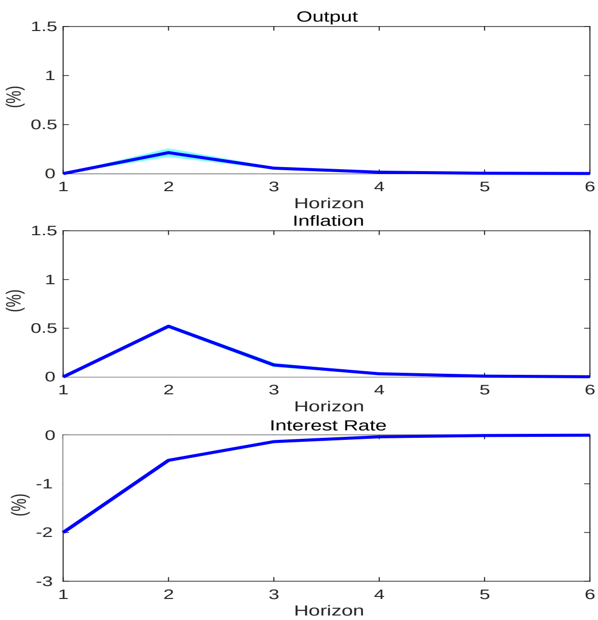
(a) Model 1 (w/o AAC and ZLB)



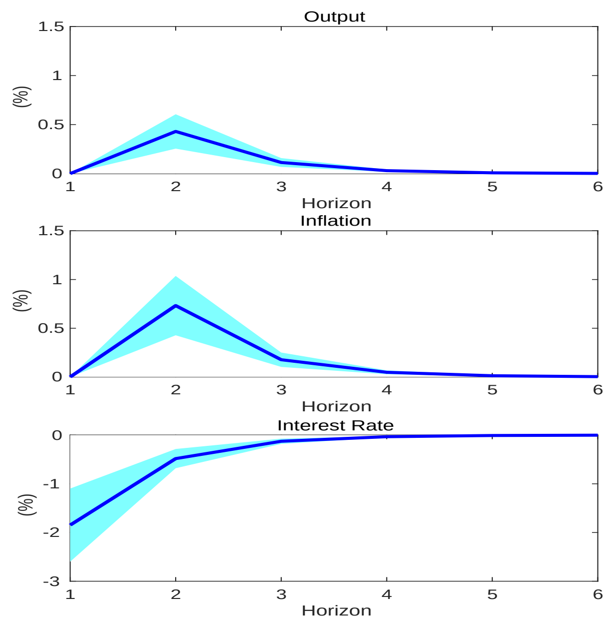
(b) Model 2 (w/ ZLB)



(c) Model 3 (w/ AAC)



(d) Model 4 (w/ AAC and ZLB)



Notes: The values of impulse response are derived using the method of generalized impulse response funtion. The blue solid line and light blue shaded area represent means and 90% interval, respectively. ZLB and AAC stand for zero lower bound and asymmetric adjustment cost, respectively.