Is the Fed Responsible? And for What?

Han Li*

This version: Oct. 2010

Abstract
Since the time the housing bubble burst and dragged the economy down to the level never experienced since the great depression, there has been a heated debate over whether the Fed’s unprecedented low interest rate over an extended period should be responsible for creating the housing bubble. Taylor (2008) pins down the loose monetary policy to be the primary reason by comparing nominal Fed funds rates with Taylor Rule prescription. Given Taylor Rule’s limitation during the time with market turmoil, this paper uses the time varying parameter model with stochastic volatility to examine whether the Fed has systematically shifted its policy rule after 2000 and whether the Fed fails to respond to potential inflation changes. Empirical results suggest that even though monetary policy is easy and accommodative in terms of the nominal interest rate but it is appropriate regarding to medium term price stability and output growth.

JEL Classification: E52

Key words: Time-varying parameter model, Taylor-rule, Forward looking monetary policy reaction function, Stochastic volatility.

*Address: The University of Kansas, Department of Economics, 415 Snow Hall, Lawrence, KS 66045.
1 Introduction

The Federal Reserve lowered its policy interest rate, Federal funds rate (FFR), from 6% to 1.75% during 2001 and kept it below two percent till the end of 2004 for nearly 36 months. This unprecedented easy money policy since World War II certainly reflects the Fed’s purposeful response to both the September 11 attacks in 2001 and the dot-com bust in 2002. However, during this so-called "too low for too long" period the housing bubble began to gather its momentum, whose inevitable burst subsequently triggered the real estate sector crisis and financial system chaos starting in 2007. There has been a heated debate since then over whether the Fed’s unprecedented low interest rate is supposed to be responsible for creating the housing bubble. Taylor (2008), for instance, argues that the Fed should take responsibility for laying the foundation for housing bubble by keeping the interest rate too low for too long and shows that the Fed funds rate has been considerably deviating from the interest rate prescribed by Taylor rule, leaving the market exposed to excessive liquidity for an extended period. Figure 1.1 and 1.2 plot the FFR against Taylor rule prescription using two different sources of data, real time data and ex post data. The former is the best knowledge that Federal open market committee (FOMC) members are informed of at the time of making interest rate decisions, while ex post data are information released to public on a regular basis with a certain time lag, not readily available to FOMC members. Both graphs\(^1\) indicate that FFR is below Taylor rule prescription\(^2\) and the latter has been proven to stabilize the economy theoretically and empirically (Clarida, Gali and Gertler.2000, CGG henceforth). However, there are two limitations related to Taylor rule prescription. The first one is fixed response to inflation changes and output gap at 1.5 and 0.5, which may not correctly describe the monetary authority’s policy stance if they decide to focus more on reducing output gap and promoting employment during the time of persistent mild inflation expectation, like what we have witnessed since mid 90s. As presented in Figure 2.1 and 3.1, monetary authority’s expectation of inflation has been mild since early 90s, while the expected output gap has been undergoing

\(^1\)Because data availability and frequency are different between real time data and ex post data, the graphs present the comparison over different range.

\(^2\)The FOMC started to use PCE (chain-type price index for personal consumption expenditures) in 2004. For Taylor rule suggested by real time data, GDP chain weighted price index is used to ensure consistency in the data. The results are not changed much if PCE is otherwise used. See Bernanke (2010)
dramatic changes after 2000 compared to 90s. On the other hand, in Figure 2.2 and Figure 3.2, actual realization of inflation and output gap are both fluctuating more than expectation of the monetary authority which may suggest the cautious use of ex post data. At the same time, we can observe that FFR movement is tracking the output gap while not in alignment with inflation movements. If emphasis was shifted towards reducing output gap between 2000 and 2003, then comparison between fixed responses prescription and FFR under this scenario would give rise to biased conclusions. Second, Taylor rule does not take a broader range of criteria into consideration, although it is consistent with dual mandates in accordance with the Federal Reserve Act. Indeed, the absence of error terms may lead to failure of capturing certain temporary deviation from price stability and full employment goal. When economy encounters sudden changes, contingent or emergent policy would be interpreted as being inappropriate by comparison to Taylor rule prescription. Therefore, to better analyze the monetary authority’s seemingly abnormal policy stance, it would be better to describe the policy by means of estimating a policy reaction function than comparing nominal interest rate and prescribed interest rate only.

Considering potentially shifted focus between price stability and full employment, many efforts have been devoted by macroeconomists to investigate the parameter stability along the time (CGG, Kim and Nelson 2006, Boivin 2004, etc.). This paper adopted a moving window scheme to estimate a forward-looking monetary policy reaction function (CGG) to shed light on time variation in monetary authority’s response to inflation and output gap. Using the rolling regression procedure with GMM method, we estimate response coefficients of inflation and output gap for Greenspan and Bernanke’s tenure\(^3\) and find there is a systematic shift in the response coefficient of inflation in the later tenure of Greenspan after 2000. Given the potential broader range of criteria The result is barely altered even after we include the asset market impact in the regression or artificially set the equilibrium real rate down to zero to reflect indirect asset market impact. However caveats with respect to this approach would contaminate or distort the results. With the presence of heteroskedasticity, if variance is assumed to be constant within the window, fluctuations of the policy shocks have to be absorbed by the coefficients. In this case, the estimated coefficients would exhibit exaggerated time variations due to unnecessary absorption of policy shocks.

\(^3\)The first window starts from 1977Q4 to 1987Q3
Therefore it would be better to adopt a more rigorous and comprehensive treatment of time variation in the parameters of monetary policy reaction function. This paper proposes a time varying parameters (TVP-SC) model with stochastic volatility in a state-space model form. State-space model approach have been used to probe the monetary policy reaction function because of its flexibility to investigate time varying policy responses and also the learning process implied by prediction variance decomposition. To establish the TVP monetary policy reaction function, three general considerations are brought to researchers’ attention: treatment of endogeneity, modeling time variation in coefficients and heteroskedasticity. First of all, endogeneity problem in estimating forward-looking monetary policy reaction function is a natural outcome of intractable expectation, which is commonly replaced by ex post observation in practice. Macroeconomists generally tackle this problem by carefully selecting instrumental variables (IVs) or using real time data from green book which is prepared for FOMC members to make decisions on interest rates. Second, time variation in coefficients can be either estimated with split sample or modelled in a state-space model form. Continuous or discrete changes define TVP or Markov switching models respectively. Third, treatment of heteroskedasticity includes imposing functional forms on variance or using heteroskedasticity robust estimators. The popular functional forms include GARCH model and stochastic volatility. Boivin (2004) explores TVP type monetary policy reaction function using real time data and heteroskedasticity robust estimators of variances. Kim and Nelson (2006) proposed a two-step procedure making use of IVs and ex post data to approach the same question. And Sims (2001) suggests that time variation in variance would be more important than time variation in a Markov-switching reduced-form model with ex post data. In this paper, a TVP model with stochastic volatility is estimated by Markov chain Monte Carlo sampling method using real time data. The merits of this model setting and estimation are elaborated in model specification section.

The organization of the rest of the paper is as follows. The next section lays out the empirical framework of our preliminary investigation and estimation results for baseline model are reported. In addition, shortcomings of preliminary approach are discussed.. Section 3 introduce the TVP with stochastic volatility model. Section 4 reports the empirical results and interpretation of the estimation. The last section concludes the paper.
2 Preliminary investigation of parameter instability

2.1 Baseline policy rule

Following CGG, we specify the Fed’s policy reaction function augmented with smoothing adjustment as

\[
\begin{align*}
  i_t &= (1 - \beta_3(L))(r^* - (\beta_1 - 1)\pi^* + \beta_1 \pi_{t,k} + \beta_2 x_{t,q}) + \beta_3(L)i_{t-1} + \varepsilon_t \\
  \varepsilon_t &= -(1 - \beta_3(L)\beta_1 (\pi_{t,k} - E[\pi_{t,k} | \Omega_t]) + \beta_2 (x_{t,q} - E[x_{t,q} | \Omega_t]) \\
\end{align*}
\]

where \(i_t\) is the effective nominal FFR. \(r^*\) is the long run equilibrium real interest rate. \(\pi^*\) is the desirable inflation level. \(\beta_3\) is the persistence of FFR adjustment. \(x_{t,q}\) and \(\pi_{t,k}\) represents annualized output and price level changes during the period between \(t\) and \(t + q\), \(t\) and \(t + k\) respectively. We estimate the model using GMM based on the orthogonality conditions

\[
E[\varepsilon_t z_t] = 0
\]

where \(z_t\) is the instrumental variables known when FFR is determined. For forward looking horizon, we use \(k = q = 1\).

2.2 Rolling regression experiments with ex post data

We first conduct undetermined multiple structural break test over the range of 1987Q3 through 2008Q4 (the Greenspan’s and Bernanke’s tenure period), using the procedure developed by Perron and Bai (1998). Then we move the window starting from 1977Q4-1987Q3\(^4\) by one quarter forward each time over the full range of data. Each regression is estimated using GMM with IVs. This approach maintains the nonlinearity structure caused by monetary authority’s intention to smooth the FFR movement and properly deals with endogeneity problem caused by replacing expectation with ex post data. The window’s length is chosen to be 10 years and instrumental

\(^4\)The focus of this paper is policy changes around 2000 within Greenspan’s tenure (1987-2004). Also the length of the window can not be reduced as small as possible because of the use of instrumental variables reduce degree of freedom.
variables include two lags of FFR, inflation, output gap, M2 money growth, commodity price index. Heteroskedasticity robust errors are reported but no functional forms for variance is specified here.

Unexpected weakening sales and production and high unemploymen at the turn of 2000 and 2001\footnote{See press release of FOMC on Jan 3, 2001.} make the monetary authority decide unanimously\footnote{In eleven of thirteen FOMC meetings involving cutting FFR, only two meetings have one vote against cut.} on quickly and preemptively cutting FFR. Then 911 terrorism attack in 2001 was followed by a series of corporate scandle, high-profile enterprises’ bankruptcy and dot-com bubble burst. These factors are important reasons that the monetary authority keep it at unprecedented low level for an extended period in order to have it work through the economy. But when asset market recovered its loss in late 2003, the monetary authority did not respond. An important question is whether it suffices to focus exclusively on the inflation and output gap’s response to evaluate the soundness of monetary policy during this period, and whether the monetary authority was tempted to response to asset market changes. The appropriate role of asset prices in the conduct of monetary policy has been discussed extensively in the literature. Cechetti et. al. (2000) argue that central banks should at times target asset prices in order to stop bubbles from getting too far out of hand while Bernanke and Gertler (1999) maintain that the Fed should not respond to movements in asset prices. Bernanke (2005).states that the Fed is neither in the good position to distinguish bubble from boom nor has the appropriate tools to prevent it from forming. Rather than asking whether or not monetary policy should target asset prices, we instead ask whether there need to be some adjustment for the policy rule regression in terms of asset prices in order to evaluate properly the Fed’s policy interest rate setting. We consider two alternative ways to do so. First, we directly add the asset price changes to the regressors in order to see whether the coefficient on the inflation gap would be altered and whether the asset price significantly enters the regression. Second, we artificially lower the long run equilibrium real policy interest rate, which is suggested by McCulley and Toloui (2008) and Taylor (2008a). With the original empirical policy rule regression (1), it is implicitly assumed that there is a stable relationship between the real policy interest rate and the actual cost of raising capital such that there exists a long run equilibrium level of raising capital when the inflation and output are both at desirable level. This relationship is largely represented by the risk premium which inevitably increases dramatically especially when the
asset prices crash. Therefore, a lower level real policy equilibrium interest rate would be well expected when financial markets are chaotic. We thus estimate the same regression model with the real policy interest rate set at zero percent level to reflect financial market distress\(^7\).

The data used in this baseline model are quarterly time series ranging from 1977:Q4 to 2008:Q4. For structural break tests, we use data from 1987Q3 to 2008Q4 to represent the Greenspan-Bernanke period, which include the great moderation during 1990s and the suspicious “deviation” period from 2000 to 2004 when the housing market is gradually forming a bubble. For the rolling regression exercise, we use data series from 1977Q4 to 2008Q4, and the first window ranges from 1977Q4 to 1987Q3 when Greenspan took the job as Chairman of Federal Reserve. The last one ranges from 1999Q1:2008:Q4. Each window covers 40 quarters. All the data are retrieved from Global Insight, otherwise indicated in the paper. For the inflation rate we use annualized rate of quarterly change of GDP deflator between two consecutive quarters. For equilibrium real policy interest rate, we use the sample mean of the real policy interest rate which is slightly higher than two percent. For the output gap, we use the deviation of unemployment rate from a fitted quadratic function of time\(^8\). This paper uses the average effective Federal Funds rate in the first month of each quarter as the actual Federal Funds rate and two measures for asset price, S&P 500 and Dow Jones Composite Average. In the baseline model the instrumental variable set include two lags of Fed funds rate, inflation, output gap, commodity price, M2 money supply.

### 2.3 Baseline results

Table 1 and 2 report the structural break test results. The hypothesis of no break point against a given fixed number breaks (from 1 to 3) is always rejected at 1% level. Also three break points are suggested for the period between 1987Q3 and 2008Q4: 1992Q1, 2000Q4, 2004Q3. These three break points coincide with outstanding economic event related to FOMC and U.S. economy. In 1992, U.S. was recovering from the nineteen months recession from Jan. 1990 to July 1991 and the Fed lowered the nominal policy interest

\(^7\)We lower the real policy interest rate to 0 percent when stock market price, represented by Dow Jones Index or S&P 500, decline by 10% from previous year.

\(^8\)As a robustness check, we also employed the percentage change from potential GDP (compiled by Congressional Budget Office), the results are not changed significantly.
rate to three percent level for the first time since 1960s. At the end of this year, Greenspan began lecturing FOMC on surge in productivity growth. Also monetary authority started to announce its interest rate target to improve transparency since then. 2000Q4 is the time that U.S. was about to enter an eight months recession starting March 2001 and ending Nov. 2001 and policy interest rate level reached its peak level at six percent. During FOMC meetings in the last quarter of 2000, robust economic growth and low unemployment is predicted. However, the bottom fell out later in 2001 and FOMC has to rush to change policy direction. Starting from July 2004, the Fed initiated a tightening cycle after thirty five months of lower-than-two-percent nominal policy interest rate and later this year Greenspan observe the seemingly decoupling of short term interest rate from long term interest rate, so called “Greenspan’s Conundrum” These specific scenarios provide a potential trigger for a systematic change in the way that central banking is conducted.

Figure 4.1 reports the rolling regression result for inflation response. We can see that during the 1990s the estimated response to the inflation was kept at a level greater than Taylor rule benchmark. During this period the one error confidence interval is quite tight. From 1992 to 1994, the coefficient exhibits a sudden increase, which has been captured by the structural break test. After 2001, the response to the inflation displays a dramatic dip and declines to the level lower than one, or even negative. This trend continues until 2005 and changed back to the level greater than one. The standard deviation of this period also increased dramatically compared to 1990s, indicating less information carried by the response to the inflation gap. From the estimates, the change from the aggressive policy to the accommodative policy stance could be justified during 2000 to 2005, but the conclusion may be contaminated by the sharp increase in the standard error. Figure 4.2 describes the estimated response to ex post output gap. As we can see that the error band is narrower between 2000 and 2003 and this suggests more information about policy interest rate changes brought by the output gap. The output response declines after 2000, and given dramatic changes in inflation coefficient, this is not unreasonable.

Figure 5 reports the rolling regression for the original regression model

\footnote{See green book report of FOMC meeting on Oct 3, Nov 15, and Dec 19}
\footnote{According to official record of proceedings of last three FOMC meetings in 2000, the three quarter ahead unemployment forecasts are 4.1%, 4.3%, 4.6%. However unemployment rose to 5.7% at the end of 2001.}
augmented with the asset price as an additional regressor. We can observe that the trend of the response to the inflation has been bent upward compared to the case in the baseline model. From 2000 to 2004 the response increases but still lower than one\(^{11}\). As for the significance of coefficients of asset price, we can see from Table 3 the response to asset price is significantly different from zero from 2002 to 2003, except which the direct effects of asset price are not significantly different from zero. Figure 6 represents the rolling regression for the baseline model with intercept adjustment. From 2001 to 2003, the response to inflation is lifted reflecting the indirect asset price effects.

### 2.4 Implications and shortcomings

Based on the evidence from structural break tests together with certain important historical events, time variation in parameters should not be neglected. However, the structural break test also has its own limitation. It cannot reveal information about the pattern that monetary authority changes its behavior. Specifically, Structural break test is unable to tell us whether monetary authority has shifted its policy to a more accommodative one or more aggressive. Similarly, it cannot distinguish unidirectional changes from changes in a symmetric way. Instability in parameters could be confirmed by structural break test but a richer explanation about instability requires rigorous treatment. The policy implication would benefit more from quantitative analysis based on a monetary policy reaction function.

As a first step of policy examination, moving window estimation for CGG monetary policy reaction function would shed some light on the direction and scale of policy changes. The estimation of CGG model by moving window with GMM approach maintains the nonlinear structure in describing monetary authority’s policy stance and suggests time variation in coefficients. Further investigation of asset market impact reveals that monetary authority may be responding to a broader range of criteria under certain circumstances (asset market turmoil between 2002 and 2003). However under current framework, policy shocks are assumed to have a constant variance within the ten-year window, hence abrupt changes are hard to capture. In addition, the window’s length cannot be shortened as much as we would

\(^{11}\)In Figure 5, we use Dow Jones Composite Index to represents asset market impact. We also tried S&P 500 index, which barely changes the results.
like, because of lagged instrumental variables. Moreover, the unaccounted changes in volatility due to the absence of a functional form of variance would exaggerate policy responses to inflation and output gap. In other words, if monetary authority had to make contingent and temporary policy changes confronted with emergency or unforeseen circumstances, these shocks have to be absorbed by the coefficients. If this is the case and we interpret policy stance by looking at the level of coefficients only, biased conclusion about monetary policy at that time may be reached. Furthermore, if the biased coefficients lower than Taylor rule benchmark, we may interpret monetary policy as inappropriate while the methodology here might be inappropriate. Other shortcomings with rolling window scheme include rigidity in selection of window’s length, sensitivity to the selection of instrumental variables, loss of degrees of freedom due to lagged instrumental variables and high standard errors caused by low degree of freedom. Therefore, to investigate the monetary authority’s behavior with full consideration in time variation and unforeseen policy shocks, it is better to consider a time-varying parameter model with stochastic volatility.

3 TVP-SV Model specification

CGG forward looking monetary policy reaction function is modified to allow for continuously time-varying coefficients and coefficients follow driftless random walk

\[ i_t = (1 - \beta_{3,t}) (\beta_{0,t} + \beta_{1,t} \pi_{t,k} + \beta_{2,t} x_{t,q}) + \beta_{3,t} i_{t-1} + \varepsilon_t \]

\[ \beta_{i,t} = \beta_{i,t-1} + \mu_{i,t} \quad i = 0, 1, 2, 3 \]

\[ \mu_t \sim i.i.d. N(0, \Sigma), \mu_t = (\mu_{0,t}, \mu_{1,t}, \mu_{2,t}, \mu_{3,t})' \]

and the log-volatility to follow an autoregressive process.

\[ \varepsilon_t \sim N(0, \sigma^2), \sigma^2_t = \gamma \exp(h_t), \]

\[ h_t = \phi h_{t-1} + \eta_t, \eta_t \sim N(0, \sigma^2_{\eta}) \]
It is assumed that $\mu_{i,t}$ and $\varepsilon_t$ are uncorrelated. Modeling time variation in coefficients and variance have been discussed in several papers. Cogley and Sargent (2001,2005) pointed out the significant role played by learning process of the Fed, even with presence of heteroskedasticity, has to be included in the model specification. Sims (1999) estimates a reduced-form equation with Markov switching process in coefficients with heteroskedasticity and emphasizes the role of time variation in variance. We consider stochastic volatility process for log-volatility because of its flexibility and richer structure compared with GARCH process of which error terms are absent.

The policy shocks $\varepsilon_t$ in the model describe either pure discretion or broader responses. Pure discretion includes psychological factors (sentiments), political pressure, reappointment pressure, rotating FOMC members and etc. These shocks would be transient and not last long or just one-time shock; therefore the realization would be implied by a larger variance. Broader responses imply that the Fed may from time to time deviate from its inflation and output targets when, for instance, asset price plumments, risk spread expands dramatically in a short time. Short term deviation is captured if we assume that variance follows stochastic volatility model. Moreover, as pointed out by Orphanides (2002), using ex post data which are information not readily available to FOMC members would lead to distortion in analysis of monetary authority’s responses to inflation and output gap or at least a distorted view against monetary authority’s original intention. He suggested using real time data, included in green book report, to represent monetary authority’s expectation of future inflation and output growth. In this paper, monthly real time data are used and detailed description is elaborated in the next section.

This model is estimated using Markov Chain Monte Carlo samplings. Details of algorithm are recorded in Nakajima (2009). There are many advantages of MCMC method. First if we take $\{\beta_{i,t}, h_t\}$ as state variables and $\{\Sigma, \phi, \sigma^2, \gamma\}$ as hyperparameters, the model forms a nonlinear state space model form, MCMC method would be a computational efficient way to estimate it. Second, it allows us to sample hyperparameters and state variables simultaneously and uncertainty of the parameters is retained while in maximum likelihood estimation, we need to take maximum likelihood estimators as known to filter the state variables. Third, with conditional sampling we can maintain the dynamics between monetary authority’s preemptive response to projected deviation from targets $\beta_{1,t}$, $\beta_{2,t}$ and smooth adjustment.
$\beta_{3,t}$, which otherwise has to be linearized and simplified.

Algorithm is described as following.

Define $\theta = \{\Sigma, \phi, \sigma_\eta, \gamma\}$, $\beta = \{\beta_{0,t}, \beta_{1,t}, \beta_{2,t}, \beta_{3,t}\}_{t=1}^n$, $h = \{h_t\}_{t=1}^n$

1. Initialize $\theta, \beta, h$;
2. Sample $\beta_{3,t} | \beta_{1,t}, \beta_{2,t}, \beta_{0,t}, \Sigma, \gamma, h, y$;
3. Sample $\beta_{1,t}, \beta_{2,t}, \beta_{0,t} | \beta_{3,t}, \Sigma, \gamma, h, y$;
4. Sample $\Sigma | \beta$;
5. Sample $h | \gamma, \phi, \sigma_\eta, \beta, y$;
6. Sample $\phi | h, \sigma_\eta$;
7. Sample $\sigma_\eta | \phi, h$;
8. Sample $\gamma | h, \beta, y$;

Prior distributions we used in sampling the state variables and hyperparameters are as following:

$$\beta \sim N(0, 10 \times I_4); \Sigma \sim IW(4, 40 \times I_4); \frac{\phi + 1}{2} \sim Beta(20, 1.5); \sigma_\eta^2 \sim IG(2, 0.02); \gamma \sim IG(2, 0.02)$$

4 Data and empirical results

The data used for the model proposed in previous section are time series constructed from green-book reports published by the Federal Reserve Board. Green book together with beige book, blue book are the materials prepared by the Federal Reserve Board staff and provided to FOMC members for reference of current economic situation in U.S. They are primary source of information used to determine the policy interest rate, Federal Funds rate. These green-book reports are made public with a five-year lag. Current available data range from 1966 to 2004. FOMC members meet generally 8-10 times a year, and each meeting generate one report. We extend the data
to monthly frequency by simple interpolation. For inflation expectation, we use three-quarter ahead projected GDP chain-weighted price index; for output gap, we apply HP filter to three-quarter ahead projected unemployment rate and take the residual series; for interest rate, we use average daily effective FFR. We sample 8000 times and discard the first 1000 to improve convergence.

Figure 7.1 to 7.4 plots the posterior mean of intercept, inflation response, output gap response and persistence in setting the policy instrument respectively. In the lower left panel, inflation response was low in 70 and has increased dramatically during late 70s and reached level above Taylor rule’s prescription of 1.5. This is consistent with CGG’s argument that the monetary authority’s attitude towards inflation is getting stronger during Volcker and Greenspan’s chairmanship; while in 70s they did not respond to inflation expectation sufficiently. During 90s, inflation response continue to be strong and consistently above Taylor rule’s prescription. This is the times when we have witnessed mild inflation and persistent economic growth, dubbed as Great Moderation. After 2000, inflation response slightly declines but is still stronger than it was in mid 90s and appropriate in terms of Taylor rule standards. The Fed’s policy interest rate is at unprecedented low level after 2001 and it is obvious that monetary authority is implementing an easy monetary policy but according to the monetary policy reaction function we estimated here, the policy interest rate is a proper response to medium term inflation expectation (three-quarter ahead forecast is used in the model).

The upper right panel depicts monetary authority’s response to expected output gap. The response is at low level in 70s and is continuously on the rise since early 80. While inflation response remained steady in 90s, output gap gained more attention from the monetary authority which is reasonable given mild inflation during 90s. After 2000, inflation response declined slightly, at the same time, the monetary authority’s efforts to reduce output gap remained high. The lower right panel plots the persistence of FFR adjustment. The monetary authority tends to smooth out their interest rate adjustment in order to mitigate market fluctuation.

In Figure 8 we plot volatility against time. The policy shock’s variance has been declining since 1972, except a spike during the experimental era between 1979 and 1982 (by Chairman Volcker). Reduced variance in policy

\(^{12}\)Early meetings may not generate three-quarter ahead forecast, and that’s why the data set used here starts from August 1972.
shocks implies that monetary authority tends to follow the dual mandates, price stability and full employment, more closely after 1982. Policy shocks tend to be further subdued in 90s. This trend coincides with increasing inflation response and output gap response indicating that monetary authority is setting up policy instrument in a more predictable way. After 2000, volatility increased again. Indeed, this reflects the potentially abrupt policy changes given a series of unforeseen economic and political events which are not and cannot be captured by greenbook data. Dot-com bubble burst followed by major asset market price plunging also would trigger temporary policy changes in response to factors other than inflation and output. Increase in discretionary behaviors under chaotic economic conditions is well captured by flexible stochastic volatility model.

Now if we compare the TVP-SV’s results here with moving window estimation results where the policy instruments were shown to be inappropriate regarding to Taylor rule, we would attribute the difference to the use of real time data which represents the best available knowledge of monetary authority and proper modelling of time variation in coefficient and variance. Reduced variation in policy shocks, if not accounted, would otherwise have been absorbed by coefficients, leading to a bias in coefficients. After 2000, the policy shock tends to be bigger compared to 90s, these changes reflect contingent and temporary policy discretion if not accounted as in moving window’s estimation would give rise to lower coefficients if the policy shock is negative. That would explain why we end up with low inflation response in moving window’s case. If we compare the TVP-SV’s results with Taylor rule prescription, we can see that if responses are forced to be constant along the time, the prescription may not be appropriate to explain the behavior in face of emergency and enormous uncertainty, especially when monetary authority’s expectation of future output and inflation may be exposed to large revisions in short or medium run. In case of early 00s, if a greater response to output gap was actually called on to accomodate real economy, the Taylor rule with fixed output responses would otherwise suggest a higher policy interest rate than actually needed.

Estimated hyperparameters are summarized in Table 4. Figure 9 evaluates convergence performance of samplers of hyperparameters. The upper panel depicts the autocorrelation functions of samples, which decline quickly and indicates diminishing autocorrelations. The middle panel draws the sample path of hyperparameters and the lower panel is posterior distribution.
5 Conclusion

This paper investigates whether the way Federal Reserve implements monetary policy has been changed since 2000 such that policy instruments fail to respond to potential inflation in accordance with Taylor rule. Structural break tests verify that policy reactions are not stable along the time; and further investigation using moving window suggests that the Fed’s response to inflation is not consistently acting in accordance with Taylor rule especially after 2000. Evidence from direct and indirect asset market impact support the idea that policy shocks are not sufficiently taken into account with absence of proper functional form for variance. Then we propose a time varying parameter with stochastic volatility model for estimating the monetary policy reaction function. This model provides proper description of time variation in coefficients and variance, and can be estimated using MCMC sampling. From the estimated results, we found that volatility has declined dramatically since 70s and reflected higher possibility of reduced policy shocks. Inflation response increases to the level above Taylor rule prescription after 1982, dipped during recession in early 90s, and rose to it peak in 1998. After 2000, the Fed’s response to medium term inflation expectation remains appropriate according to Taylor rule standards, even though weaker compared to late 90s. For the same period, output gap response continue the tendency of ascension. With inflation largely contained during 90s, the Fed assigned more weights on improving employment and productivity growth. As for period after 2000, facing unexpected growth falling down with a series of negative events in both business and politics, the Fed seemingly continued to put more emphasis on reducing output gap. With policy shocks properly accounted using stochastic volatility model and real time data, we shed lights on policy stances during 2000-2003. We think that even though the policy instruments are at historically low level, but they are appropriate given best knowledge of inflation and output gap projection at that time and due consideration of policy discretion in face of market turmoil.
References


Table 1: Tests against fixed number of breaks in Clarida et.al.(2000) model

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Statistics</th>
<th>C.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 versus 1 break</td>
<td>254.28</td>
<td>15.37</td>
</tr>
<tr>
<td>0 versus 2 breaks</td>
<td>130.96</td>
<td>12.15</td>
</tr>
<tr>
<td>0 versus 3 breaks</td>
<td>849.05</td>
<td>10.27</td>
</tr>
</tbody>
</table>

Note: The estimation is for Greenspan-Bernanke(87-08) tenure using ex post data.

Table 2: Break points in Clarida et.al.(2000) model

<table>
<thead>
<tr>
<th>Model</th>
<th>SSR</th>
<th>Break point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Break</td>
<td>17.84</td>
<td>2004Q3</td>
</tr>
<tr>
<td>2 Breaks</td>
<td>13.30</td>
<td>2004Q3,2000Q4</td>
</tr>
<tr>
<td>3 Breaks</td>
<td>10.02</td>
<td>2004Q3,2000Q4,1992Q1</td>
</tr>
</tbody>
</table>

Note: The estimation is for Greenspan-Bernanke(87-08) tenure.
<table>
<thead>
<tr>
<th>Year</th>
<th>S&amp;P</th>
<th>Dow Jones</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002: Q1</td>
<td>0.058*</td>
<td>n.a.</td>
</tr>
<tr>
<td>2002: Q2</td>
<td>0.087**</td>
<td>0.044*</td>
</tr>
<tr>
<td>2002: Q3</td>
<td>0.063**</td>
<td>0.035*</td>
</tr>
<tr>
<td>2002: Q4</td>
<td>0.081**</td>
<td>0.047**</td>
</tr>
<tr>
<td>2003: Q1</td>
<td>0.101**</td>
<td>0.071**</td>
</tr>
<tr>
<td>2003: Q2</td>
<td>0.100**</td>
<td>0.076**</td>
</tr>
<tr>
<td>2003: Q3</td>
<td>0.106**</td>
<td>0.071**</td>
</tr>
<tr>
<td>2003: Q4</td>
<td>0.115**</td>
<td>0.076**</td>
</tr>
</tbody>
</table>

Notes: 1. **, * indicates statistical significance at a 98% and 90% level
2. Moving window starts from 77Q1-87Q1; model is estimated using GMM with IVs
3. We focus asset market's significant impact during period between 99-08
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Std.Dev</th>
<th>95%L</th>
<th>95%U</th>
<th>Geweke</th>
<th>Inef.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0^2$</td>
<td>0.0379</td>
<td>0.0626</td>
<td>0.0082</td>
<td>0.0593</td>
<td>0.703</td>
<td>193.63</td>
</tr>
<tr>
<td>$\alpha_1^2$</td>
<td>0.0244</td>
<td>0.0547</td>
<td>0.0055</td>
<td>0.0275</td>
<td>0.094</td>
<td>203.82</td>
</tr>
<tr>
<td>$\alpha_2^2$</td>
<td>0.0347</td>
<td>0.0456</td>
<td>0.0074</td>
<td>0.0583</td>
<td>0.888</td>
<td>166.56</td>
</tr>
<tr>
<td>$\alpha_3^2$</td>
<td>0.0069</td>
<td>0.0054</td>
<td>0.0030</td>
<td>0.0109</td>
<td>0.529</td>
<td>132.23</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.9993</td>
<td>0.0005</td>
<td>0.9988</td>
<td>0.9998</td>
<td>0.009</td>
<td>19.55</td>
</tr>
<tr>
<td>$\sigma_{\tilde{\eta}}^2$</td>
<td>0.2757</td>
<td>0.0415</td>
<td>0.2336</td>
<td>0.3187</td>
<td>0.016</td>
<td>105.39</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.304</td>
<td>22.27</td>
</tr>
</tbody>
</table>
Figure 1.1 Taylor Rule w/ Ex post data v.s. FFR

Note: For ex post inflation, we use GDP deflator; for output gap, we use annualized percentage change from CBO potential GDP. The data frequency is quarterly.

Figure 1.2 Taylor Rule w/ Real Time Data v.s. FFR

Note: For real time inflation, we use three-quarter ahead projected GDP chain-weighted price index; for real time output gap, we use output gap generated from three-quarter ahead projected unemployment rate. The frequency of data is monthly.
Figure 2.1 Ex Post Inflation v.s. FFR

Note: For ex post inflation, we use GDP deflator. The frequency of data is quarterly.

Figure 2.2 Real Time Inflation Expectation v.s. FFR

Note: For real time inflation, we use three-quarter ahead projected GDP chain-weighted price index. The frequency of data is monthly.
Figure 3.1 Ex Post Output Gap v.s. FFR

Note: For output gap, we use annualized percentage change from CBO potential GDP. The data frequency is quarterly.

Figure 3.2. Real Time Expected Output Gap v.s. FFR

Note: For real time output gap, we use output gap generated from three-quarter ahead projected unemployment rate. The frequency of data is monthly.
Figure 4.1 Time Variation of Inflation Response during Greenspan-Bernanke Tenure
Estimated using Moving Window

Notes:
1. Dashed line represents benchmark response.
2. Dotted line represents one error confidence interval.
4. CBO potential GDP is used to measure output gap, and GDP deflator for inflation.
5. IVs include 2 lags of FFR, inflation, output gap, M2 money growth, commodity price index.
6. Estimation is based on Clarida et.al.(2000) model and data is ex post.
Figure 4.2 Time Variation of Output Gap Response during Greenspan-Bernanke Tenure estimated using Moving window

Notes:
1. Dashed line represents benchmark response.
2. Dotted line represents one error confidence interval.
4. CBO potential GDP is used to measure output gap, and GDP deflator for inflation.
5. IVs include 2 lags of FFR, inflation, output gap, M2 money growth, commodity price index.
6. Estimation is based on Clarida et al. (2000) model and data is ex post.
Figure 5 Time Variation of Inflation Response from 99-08 with Presence of Asset Market Direct Impact

Notes:
1. Estimation is based on Clarida et.al.(2000) augmented with asset market direct impact using ex post data.
2. Moving window is 10 years; IVs include 2 lags of FFR, inflation, outputgap, M2 growth, commodity price, and asset market direct impact.
3. Asset market direct impact is measured by percentage change in Dow Jones Composite Index
Figure 6 Time Variation of Inflation Response from 99-08 with Presence of Asset Market Indirect Impact

Notes:
1. Estimation is based on Clarida et.al.(2000) augmented with asset market indirect impact using ex post data.
2. Moving window is 10 years; IVs include 2 lags of FFR, inflation, outputgap, M2 growth, commodity price, and asset market indirect impact.
3. Asset market indirect impact is proxied by setting real interest rate to zero when asset price drop by 10% annually.
Figure 7.1 Time Varying Response to Inflation

Note: Shaded area indicates NBER recession;

Figure 7.2 Time Varying Response to Output Gap

Note: Shaded area indicates NBER recession;
Figure 7.3 Time Varying Intercept

Note: Shaded area indicates NBER recession;

Figure 7.4 Time Varying Persistence

Note: Shaded area indicates NBER recession;
Figure 8 Log-Volatility of TVP-SC Model.

Note: Posterior log volatility with one error band.
Figure 9. Convergence Evaluation of the Hyperparameters

Note: Upper panel represents autocorrelation of samples; middle panel represents sample path; lower panel represents posterior density.