Monetary Policy Rules and Macroeconomic Stability: some new evidence[*]

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This version: November 13, 2008

[*]An earlier version of this paper (July 2007) was entitled: "Testing for indeterminacy in US monetary policy". I would like to thank Mark Gertler, Peter Howitt, Frank Kleibergen, Thomas Lubik, Frank Schorfheide and seminar participants at the New York Fed, the NBER summer institute, the University of Pennsylvania and Carleton university, for comments, help and advice.

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Abstract

This paper revisits the question of indeterminacy in U.S. monetary policy using limited-information identification-robust methods. I find that the conclusions of Clarida, Galí, and Gertler (2000) that policy was inactive before 1979 are robust, but the evidence over the Volcker-Greenspan periods is inconclusive. I show that this is in fact what one would expect if policy were indeed active over that period. Problems of identification also arise because policy reaction has been more gradual recently. At a methodological level, the paper demonstrates that identification issues should be taken seriously, and that identification-robust methods can be informative even when they produce wide confidence sets.

Keywords: GMM, identification, rational expectations, DSGE models

JEL classification: C22, E31

1 Introduction

In a seminal paper, Clarida, Galí, and Gertler (2000) studied the implications of monetary policy for macroeconomic fluctuations using a prototypical forward-looking sticky price model of the monetary transmission mechanism. They proposed simple forward-looking equations for the reaction function of monetary policy to deviations of inflation and output from their implicit targets. They estimated these equations over sample periods before and after Paul Volcker became chairman of the Fed. They found that the policy rate did not react sufficiently strongly to expected deviations of inflation from target prior to Volcker, thus violating the Taylor principle and opening up the possibility of sunspot fluctuations induced by self-fulfilling expectations. In contrast, policy over the Volcker-Greenspan era was found to satisfy the Taylor principle, and this was seen as an important factor contributing to the conquest of US inflation.[1]

The objective of the present study is to revisit the original contribution of Clarida, Galí, and Gertler (2000) and re-examine their empirical findings, in the light of recent concerns over the identifiability of the model's parameters, see Canova and Sala (2005), Cochrane (2007) and Mavroeidis (2004). In this paper, I follow closely the limited-information approach of Clarida, Galí, and Gertler (2000), which makes minimal assumptions about the nature of macroeconomic dynamics. The key difference is that I use the statistical methods proposed by Stock and Wright (2000) and Kleibergen (2005), which are robust to identification failure.

The results of this paper can be summarized as follows. I find that the conclusion that policy reaction did not satisfy the conditions for determinacy (the Taylor principle)

[1] These conclusions are not uncontroversial, and there has been no shortage of alternative explanations. Orphanides (2002) emphasized the implications of using revised rather than real-time data. Primiceri (2006) and Sargent (1999) emphasized the role learning by policy makers about the behavior of the economy. Sims and Zha (2006) emphasized regime switching in volatility, rather than the parameters of the reaction function, but note that Benati and Surico (2007) reported problems with identifying policy regime switches using vector autoregressions. This list is by no means exhaustive.

before Volcker is robust to identification failure. In fact, the policy rule parameters appear to be well-identified in the pre-Volcker sample. In contrast, in subsequent periods the identification-robust confidence sets are much larger, indicating that the policy reaction function is not well-identified. Despite the fact that the point estimates lie firmly in the determinacy region, the data is consistent also with the opposite view that policy remained inactive after 1979, too.

I then argue that these findings are in fact very informative. The sharp contrast in the results between the two periods indicates a shift in the dynamics of the economy, which is highly consistent with the view that policy was unsuccessful in reigning over self-fulfilling expectations before 1979, thus generating sufficient variation in expected inflation and the output gap to identify the feedback coefficients in the policy rule. In contrast, the weak identifiability over the Volcker-Greenspan sample could well be a consequence of monetary policy that led to a determinate equilibrium, since such a policy removes sunspot fluctuations which are a potentially important source of variation in the expectations of inflation and the output gap. Leeper (1991) also made the point, in a related context, that under determinacy, policy rule parameters are not identifiable. However, I point out that weak identification may also arise under indeterminacy due to changes in the dynamics of the economy that are not caused by active monetary policy. Hence, it is not possible to infer from the weak identification of the policy rule after 1979 that policy was in fact active. Thus, my analysis points out the limitations of this limited-information approach, and the need to make use of further identifying assumptions derived perhaps from the full structure of the model (namely, the restriction that policy shocks are uncorrelated with other macroeconomic shocks), as was done by Lubik and Schorfheide (2004).

There is another possible explanation for the finding that the reaction function coefficients are not sufficiently accurately estimable after 1979 to rule out the possibility of indeterminacy.

When interest rates adjust too slowly to deviations of expected output and inflation from target, it becomes difficult to pin down the reaction function parameters accurately. I refer to this problem as excess smoothing of interest rate changes or excess policy inertia. Point estimates over different samples indicate that the degree of smoothing increased from 0.68 before 1979 to 0.92 over the Greenspan sample.

At a methodological level, the paper demonstrates two things. Firstly, there is a clear need to use identification-robust methods for inference in dynamic stochastic general equilibrium (DSGE) models, since conclusions can differ sharply from those reached by non-robust methods when identification fails.[2] Secondly, even if confidence sets turn out to be large, they can still be highly informative and admit interesting and useful economic interpretations.

The plan of the paper is as follows. Section 2 presents the model and characterizes equilibrium indeterminacy. Section 3 contrasts the empirical evidence on the policy reaction function coefficients using identification-robust and non-robust methods. Section 4 provides several explanations for why the policy reaction function is better identified in the pre-Volcker period than afterwards. Finally, section 5 offers some concluding remarks.

2 The model

2.1 Monetary policy rules

I consider a forward-looking policy rule of the type proposed by Clarida, Galí, and Gertler (2000):

$$r_t^* = r^* + \psi_\pi E_t\left(\pi_{t+1} - \pi^*\right) + \psi_x x_t \tag{1}$$

[2] The use of identification-robust methods in empirical macroeconomics has been very limited. Notable exceptions are papers on the Phillips curve by Dufour, Khalaf, and Kichian (2006), Ma (2002) and Nason and Smith (2005).

where r_t^* denotes the target nominal policy rate, π_t and x_t denote inflation and the output gap, respectively, E_t denotes expectations conditional on information available at time t, π^* denotes the inflation target and r^* is the level of the nominal interest rate when inflation and output are expected to be on target. In line with the rest of the literature, I assume that the actual nominal rate r_t may deviate unexpectedly from the target rate r_t^* for exogenous reasons and that monetary authority smooths changes in r_t. Thus, the actual rate adjusts partially to the target given by equation (1) according to $r_t = \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1-\rho) r_t^* + \varepsilon_{r,t}$. The parameter $\rho = \rho_1 + \rho_2$ can be thought of as a measure of policy inertia, or interest rate smoothing, and $\varepsilon_{r,t}$ is a monetary policy shock, assumed to be an innovation with respect to all publicly available information at time $t-1$, i.e., $E_{t-1}\varepsilon_{r,t} = 0$. This gives rise to the baseline specification of the policy rule equation in Clarida, Galí, and Gertler (2000), which can be written as:

$$r_t = \alpha + \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1-\rho)\left(\psi_\pi E_t \pi_{t+1} + \psi_x x_t\right) + \varepsilon_{r,t}. \tag{2}$$

where $\alpha = (1-\rho)(r^* - \psi_\pi \pi^*)$. When $\rho_2 = 0$, this equation coincides with the model discussed extensively in Woodford (2003, chapter 4).

Replacing expectations by realizations, equation (2) can be re-written as

$$r_t = \alpha + \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1-\rho)\left(\psi_\pi \pi_{t+1} + \psi_x x_t\right) + e_t, \tag{3}$$

$$e_t = \varepsilon_{r,t} - (1-\rho)\psi_\pi\left(\pi_{t+1} - E_t\pi_{t+1}\right). \tag{4}$$

The residual term e_t may be autocorrelated at lag 1. The assumption of rational expectations together with $E_{t-1}\varepsilon_{r,t} = 0$ give rise to the moment conditions $EZ_t e_t = 0$ for any predetermined variable Z_t.[3]

[3]This identifying assumption is not uncontroversial, see Cochrane (2007). To the extent that the model is

2.2 The transmission mechanism

To discuss the implications of the monetary policy rule (2) for macroeconomic fluctuations, I need a model of the monetary transmission mechanism. For this purpose, I choose the prototypical new Keynesian sticky price model used by Clarida, Galí, and Gertler (2000) and Lubik and Schorfheide (2004). After log-linearization around the steady state, the model's equilibrium conditions are given by

$$\pi_t = \beta E_t \pi_{t+1} + \lambda (y_t - z_t) \tag{5}$$

$$y_t = E_t y_{t+1} - \sigma (r_t - E_t \pi_{t+1}) + g_t \tag{6}$$

Equation (5) is a forward-looking Phillips curve that incorporates nominal rigidities captured in the slope parameter $\lambda > 0$, the parameter $0 < \beta < 1$ is a discount factor and the process z_t captures exogenous shifts to the marginal costs of production. Equation (6) is an Euler equation for output, y_t, derived from households' intertemporal optimization. The parameter σ is the intertemporal elasticity of substitution and the process g_t captures exogenous shifts in preferences and government spending. These equations can be derived by loglinear approximation around the steady state of a dynamic stochastic general equilibrium model, see Woodford (2003, Chapter 4).[4]

The model consisting of equations (5), (6), (2) and the identity $x_t = y_t - z_t$ can be solved to determine the path of the endogenous variables π_t, x_t r_t as a function of the exogenous forcing variables z_t, g_t and $\varepsilon_{r,t}$. If there exists a unique stable solution, the equilibrium is determinate. Indeterminacy arises whenever there exist multiple stable solutions. Woodford

overidentified, this assumption is partially testable via a test of overidentifying restrictions. The next section offers identification-robust tests of the validity of these restrictions.

[4] Uninteresting constants relating to the inflation target and the long-run equilibrium real rate have been omitted.

(2003, Proposition 4.6) shows that a necessary condition for determinacy in this model is given by

$$\psi_\pi + \frac{1-\beta}{\lambda}\psi_x - 1 \geq 0. \tag{7}$$

This can be thought of as a generalization of the Taylor (1993) principle, that nominal rates must rise by more than one for one with inflation to prevent self-fulfilling cycles. Condition (7) would also be sufficient for determinacy if the forward-looking Taylor rule (1) were replaced by a contemporaneous rule by substituting π_t for $E_t\pi_{t+1}$, see Woodford (2003, Proposition 4.4) and Lubik and Schorfheide (2004). For the forward-looking rule (2), determinacy also requires that the response to inflation should not be too large.[5] For typical values of the structural parameters β, λ, σ (e.g., the ones used by Clarida, Galí, and Gertler (2000)) and the confidence sets for ψ_π, ψ_x that are derived below, it turns out that this additional condition is not empirically binding. So, to discuss the question of indeterminacy, it suffices to focus on the condition given by equation (7).

3 Inference on the feedback coefficients

3.1 The story of Clarida Gali and Gertler

Clarida, Galí, and Gertler (2000) estimated the policy rule (2) using quarterly data from 1960 to 1997. Their results pointed to substantial differences in the estimated rule across periods. In particular, they found that interest rate policy appears to have been much more sensitive to changes in expected inflation after 1979 than it was before. To examine the implications of the estimated rules for the equilibrium dynamics of inflation and output, they then checked the condition for determinacy given in equation (7) across periods. This

[5] Woodford (2003, Proposition 4.6) provides an analytical expression of this additional condition in the special case where $\rho_2 = 0$ in eq. (2).

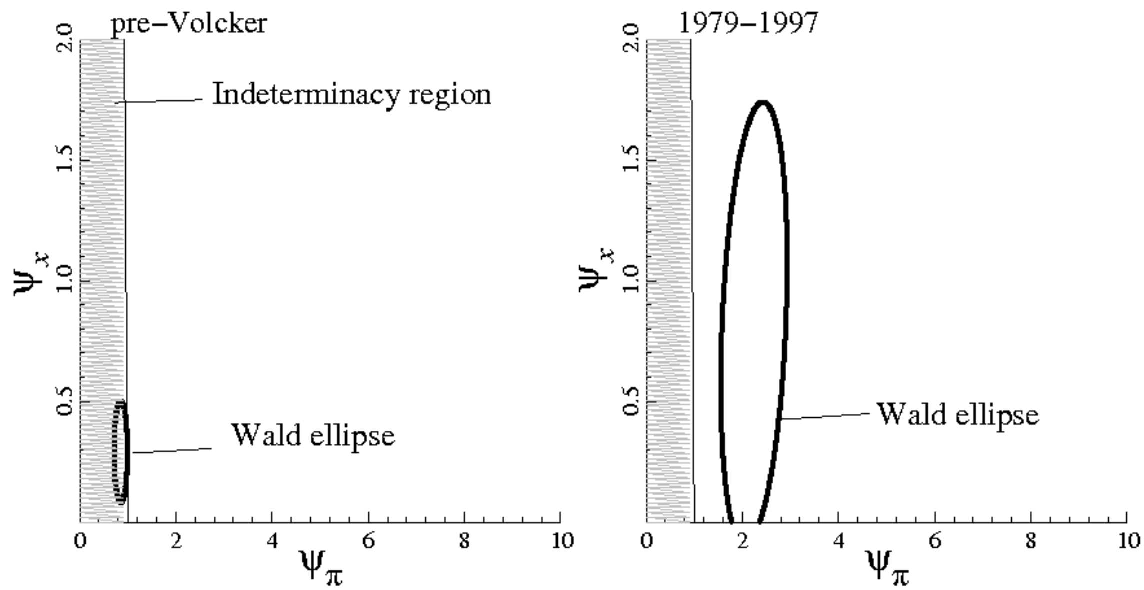

Figure 1: 90% level Wald confidence sets for the feedback coefficients (ψ_π, ψ_x) in the Taylor rule $r_t = \alpha + \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1-\rho)(\psi_\pi E_t \pi_{t+1} + \psi_x x_t) + \varepsilon_t$. The model is estimated by GMM using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix. The pre-Volcker sample is 1961:q1 to 1979:q2, and $\rho_2 = 0$ for the 1979-1997 sample.

requires knowledge of the parameters of the Phillips curve (5) β and λ. Clarida, Galí, and Gertler (2000) fixed the discount rate β to 0.99 and λ to 0.3. Given those values, they found that the point estimates of the reaction coefficients (ψ_π, ψ_x) lie in the indeterminacy region prior to Volcker's chairmanship of the Fed, whereas they lie in the determinacy region thereafter.

This conclusion can be shown more formally by constructing two-dimensional confidence sets on the parameters (ψ_π, ψ_x). I use the same data and methods as Clarida, Galí, and Gertler (2000): GMM using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix. The pre-Volcker sample covers the period 1961:q1 to 1979:q2, and the post Volcker sample runs until 1997:q4. Figure 1 presents the 90% level confidence ellipses based on inverting the Wald test on (ψ_π, ψ_x) over the two key subsamples that they studied. The confidence set for the pre-Volcker sample lies entirely within the indeterminacy region. This provides strong support for the view that policy prior to that period had been passive and had opened up the possibility of sunspot fluctuations induced by self-fulfilling expectations. Moreover, this conclusion is reached irrespective of whether one chooses to test the null hypothesis of determinacy or indeterminacy. In contrast, the confidence set for the Volcker-Greenspan sample, though considerably wider, lies firmly within the determinacy region. This again seems to provide strong evidence that policy over that period satisfied the Taylor principle, see equation (7).

It is important to point out that the above conclusions do not take into account any uncertainty associated with the chosen values for the discount factor β and slope of the Phillips curve λ. It is clear from equation (7) that the boundary of the indeterminacy region will rotate anti-clockwise around the point $(\psi_\pi, \psi_x) = (1, 0)$ as $(1 - \beta)/\lambda$ increases. Thus, smaller values of λ and/or β could alter the conclusion that there was indeterminacy before Volcker, though they would not affect the conclusion of determinacy thereafter.

It is by now well-known that DSGE models may suffer from weak identification, especially when they are estimated using single-equation methods (see Lubik and Schorfheide 2004) and results based on conventional GMM tests could be very misleading, see e.g., Canova and Sala (2005), and Mavroeidis (2004). Therefore, it is important to re-examine the above conclusions using identification-robust methods.

3.2 Identification-robust inference

I shall give only a brief description of the identification-robust methods that I use in this paper. For a detailed account of these methods, the reader is referred to the excellent surveys by Stock, Wright, and Yogo (2002), Dufour (2003) or Andrews and Stock (2005). The simplest method for obtaining identification-robust confidence sets is based on the S statistic proposed by Stock and Wright (2000). This statistic is equal to the GMM objective function evaluated at the value of the parameters under the null hypothesis and it therefore tests the validity of the moment conditions under the null hypothesis. Because this is a generalization to GMM of a test proposed by Anderson and Rubin (1949) for linear instrumental variables models, I refer to it as the AR-S statistic. One weakness of this test is that it is less powerful than the Wald test when identification is strong. To address this issue, I use the conditional score statistic proposed by Kleibergen (2005), denoted K-LM, which can be thought of as a version of the AR-S statistic that only uses an optimal combination of the instruments.

Confidence sets with confidence level 90% for the parameters ψ_π and ψ_x in the policy rule (2) are constructed by inverting each test as follows. I let ψ_π and ψ_x vary from 0 to 10 and 0 to 2 respectively, and I collect all the points (ψ_π^0, ψ_x^0) in this set that are not rejected by each test at the 10% level of significance.[6] Note that the AR-S confidence set is the collection of all the values of the parameters at which the model's identifying restrictions are not rejected at the given level of significance. Therefore, in addition to providing an identification-robust confidence set for the parameters, the AR-S statistic also provides an identification-robust test of the validity of the overidentifying restrictions, as explained in Stock and Wright (2000). In fact, the AR-S confidence sets are non-empty for all subsamples considered, indicating that there is no evidence against the identifying assumptions used in this paper.

Figure 2 presents 90% level confidence sets for the policy rule parameters (ψ_π, ψ_x) based on inverting the K-LM test.[7] Results based on the AR-S statistic are similar, and therefore omitted. The Wald ellipse is superimposed for comparison.

In the pre-Volcker sample, the identification-robust confidence set lies mostly in the

[6] The remaining parameters α and ρ_i in eq. (2) are well-identified when ψ_π and ψ_x are fixed. So, following Stock and Wright (2000) and Kleibergen (2005), they are replaced by the restricted estimates $\hat{\alpha}\left(\psi_\pi^0, \psi_x^0\right)$ and $\hat{\rho}_i\left(\psi_\pi^0, \psi_x^0\right)$.

[7] The K-LM confidence set reported here is actually based on the combination of a 9% level K-LM and a 1% JKLM test, as suggested by Kleibergen (2005). This is a device that improves the power of the K-LM test against irrelevant alternatives at which the overidentifying restrictions are violated.

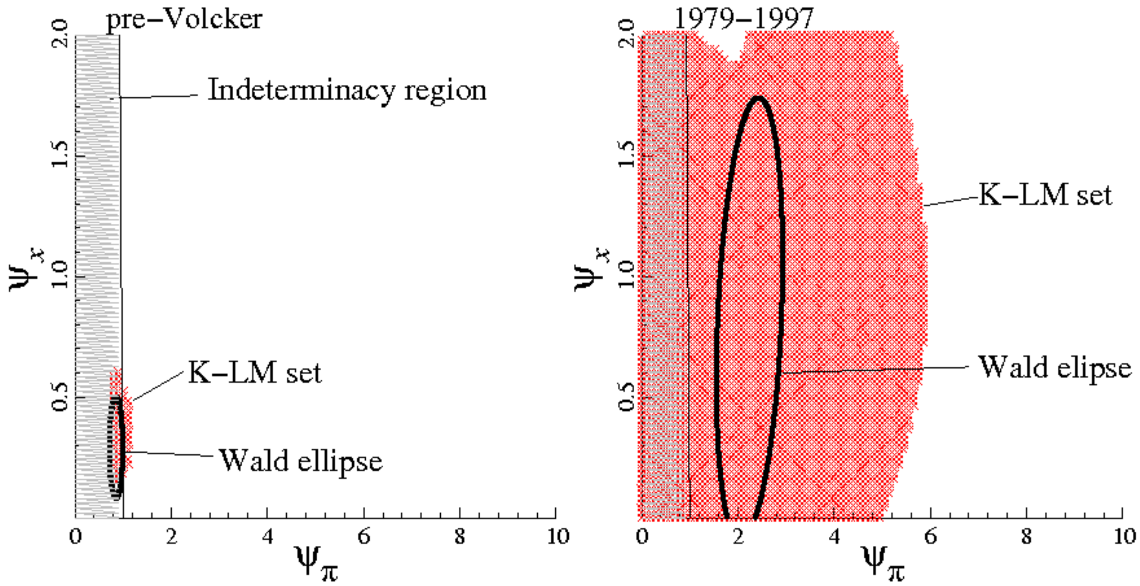

Figure 2: 90% level identification-robust confidence sets and Wald confidence ellipses for the feedback coefficients in the Taylor rule.

indeterminacy region, though it contains some values of the parameters in the determinacy region, conditional on the values $\beta = 0.99$ and $\lambda = 0.3$. In fact, the identification-robust confidence set is very similar to the Wald confidence ellipse, and this can be interpreted as evidence that the parameters of the model are well-identified over that period. Thus, the earlier finding that monetary policy before Volcker violated the Taylor principle appears to be robust to the quality of the instruments.

Note that this conclusion on indeterminacy is also reached by Benati (2007) using an entirely different approach. Benati observes that money should have predictive content for inflation, the output gap and the interest rate only in the presence of sunspot fluctuations. Thus, without estimating any structural model, Benati is able to reject the hypothesis of determinacy by finding that money Granger-causes inflation, the output gap, and interest rates before 1979.

The identification-robust confidence set for the period 1979-1997, which is reported on the right-hand panel of Figure 2, stands in stark contrast to the non-robust Wald confidence ellipse. Upon comparison with the pre-Volcker sample, it is clear that the parameters (ψ_π, ψ_x) are less accurately estimated. However, the Wald ellipse fails to reflect the amount of uncertainty about the parameters, since it is much smaller than the identification-robust confidence set. This result shows that the feedback coefficients are not sufficiently accurately estimable over that period to provide conclusive evidence on the question of inderminacy.

One may ask how these conclusions might change if we looked at different subsamples, as it was done by Clarida, Galí, and Gertler (2000). However, these authors focused mainly on point estimates, while the emphasis of this paper is on confidence sets, and these typically get larger when the sample size is reduced. Therefore, there is little scope in trying to infer policy changes in the immediate aftermath of a change in the chairmanship of the Fed. There is just not enough data to get conclusive inference over such short periods of time.

It is interesting to see if the results change when the forward-looking policy rule is estimated over the period of Greenspan's tenure, 1987q3 to 2006q1. This is motivated by the well-known fact that monetary policy over much of Volcker's tenure was designed to control money rather than interest rates, and this led to significant volatility in the policy rate, which is reflected in the variance of the residuals in the policy rule over that period. Moreover, the full Greenspan sample is roughly of the same size as those reported in Figure 2, so that any differences in the identification of the feedback coefficients cannot not be attributed to differences in the size of the samples.

When the model is estimated over the Greenspan sample, the identification-robust confidence sets do, in fact, get considerably smaller than over the 1979-1997 sample. To a large extent, this can be explained by the large fall in the variability of the residual e_t in the policy rule regression (3), which is evident from Figure 3. Recall that this residual is composed of the monetary policy shock $\varepsilon_{r,t}$ as well as the forecast errors in inflation and the output gap,

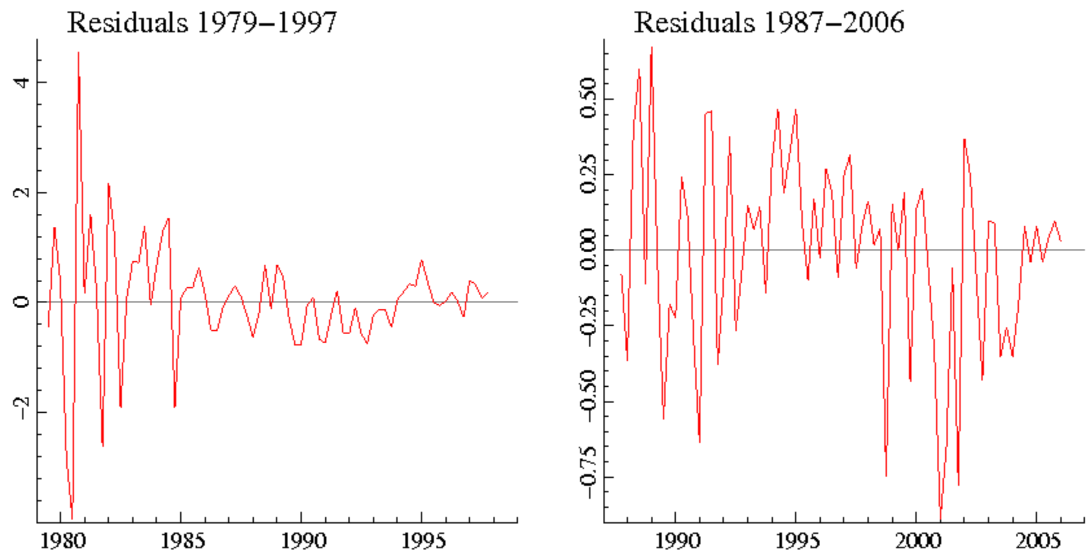

Figure 3: Residuals of the policy rule when the parameters are estimated by GMM over the two periods.

see equation (4), so this drop in volatility could arise from different sources. However, the identification-robust confidence sets over the Greenspan sample are still much wider than over the pre-Volcker period, and the Wald ellipse still understates the estimation uncertainty in the feedback coefficients, indicating that they remain weakly identified. Moreover, similarly to the picture reported on the right panel of Figure 2, the feedback coefficients cannot be estimated sufficiently accurately to rule out the possibility of indeterminacy.

3.3 Economic interpretation of the results

An initial reading of the right-hand panel of Figure 2 suggests that the conclusion that policy under Volcker and Greenspan satisfied the Taylor principle is not robust, and that the data could be consistent with either this or the opposite view. In other words, the pictures indicate that the post-1979 sample is completely uninformative about this issue.

However, I will argue that the above results are in fact informative. The key to this realization lies in the very source of identification problems, which is directly linked to the question of determinacy. As I shall demonstrate in the following section, identification problems are more likely to arise when the equilibrium of the economy is determinate. The intuition for this is simple. Good policy removes the possibility of sunspot dynamics, as well as mitigates the effects of shocks on future inflation and output. As a result, the expectations of these variables become less variable than they might otherwise be. This interpretation of Figure 2 is very much in line with the view that policy pre-Volcker destabilized expectations. This, in turn, provided sufficient variation in expected inflation and the output gap to identify the parameters of the Taylor rule. After 1979, sunspot dynamics may have subsided which explains why the reaction function is poorly identified. Thus, even though I am unable to formally reject the hypothesis of indeterminacy, the results are suggestive of a clear break in the nature of macroeconomic fluctuations around 1979 which is consistent with a switch from an indeterminate to a determinate state.

4 Discussion of identification

In this section, I discuss various explanations for the finding that the reaction function coefficients are better identified before than after 1979, and I formalize the interpretations of the empirical findings reported in the previous section. I base my discussion on the canonical new Keynesian model of the transmission mechanism presented in section 2, because it is sufficient to gain useful insights into the sources of identification in this model. Specifically, I show that identification depends on the slope of the Phillips curve, the dynamics of the shocks, and the incidence of sunspot fluctuations. I argue that, other things equal, sunspot fluctuations improve the identifiability of the reaction function coefficients, but I also observe that other things have not been equal over this period. In particular, I discuss how changes in the degree of policy inertia affect the identification of the reaction function coefficients.

4.1 Identification of the policy rule in the canonical new Keynesian model

In the ensuing discussion, I make the simplifying assumption that there are no policy inertia, i.e., I set $\rho_1 = \rho_2 = \rho = 0$ in the baseline model given by equation (2). This is done purely for the sake of clarity and tractability, and it does not affect the gist of my arguments.

To examine the identification of the policy rule in an intuitive way, it is convenient to rewrite the model as

$$r_t = \alpha + \psi_\pi E_{t-1}\pi_{t+1} + \psi_x E_{t-1}x_t + \widetilde{e}_t, \quad \text{where} \tag{8}$$

$$\widetilde{e}_t = \varepsilon_{r,t} + \psi_\pi \left([E_t\pi_{t+1} - E_{t-1}\pi_{t+1}]\right) + \psi_x \left(E_t x_t - E_{t-1}x_t\right).$$

Equation (8) could be thought of as the infeasible (since $E_{t-1}\pi_{t+1}$ and $E_{t-1}x_t$ are unobserved) second stage of an instrumental variables regression procedure. Suppose we actually observed the variables $E_{t-1}\pi_{t+1}$ and $E_{t-1}x_t$, which are the optimal instruments in this case. The rank condition for identification is the familiar lack of perfect multicollinearity between the regressors $E_{t-1}\pi_{t+1}$, $E_{t-1}x_t$. Moreover, identification is stronger, that is, the coefficients can be estimated more accurately, the higher is the exogenous variation in $E_{t-1}\pi_{t+1}$ and $E_{t-1}x_t$. This was already stressed in Clarida Gali and Gertler (1998, 2000).

Notice that, since $\beta < 1$, the Phillips curve (5) can be solved forward to yield the non-explosive solution

$$\pi_t = \lambda \sum_{j=0}^{\infty} \beta^j E_t x_{t+j}. \tag{9}$$

From equation (9), it is clear that a necessary condition for identification is that $\lambda \neq 0$. That is, the Phillips curve should not be completely flat, since if this were the case, $E_{t-1}\pi_{t+1}$ would be constant and thus trivially collinear with the intercept in the policy rule equation. This corresponds to the limiting case in which prices are completely fixed, and it is, therefore, not surprising that there would be no variation in inflation expectations. Even though this case may be ruled out as implausible, the important point is that we would expect identification of the policy rule coefficients to be weaker when the Phillips curve is relatively flat, which appears to be empirically relevant, see for example Kleibergen and Mavroeidis (2008). Note that this point is independent of the dynamics of the output gap, or the question of determinacy, and it would remain valid even if the Phillips curve contained a serially uncorrelated cost-push shock, since such a shock would not affect expectations of future inflation.[8]

When $\lambda \neq 0$, identification depends on the equilibrium dynamics of the output gap. It is well-known that, in linear rational expectations models, the equilibrium dynamics of the endogenous variables admit a linear state-space representation, see Sims (2002). Specifically, the dynamics of the output gap can be characterized by the equations $x_t = Gs_t + v_t$ and $s_t = Qs_{t-1} + \varphi_t$, where s_t is a vector of state variables, v_t and φ_t are innovations, and G and Q are functions of the structural parameters. This representation, combined with equation (9), implies that $E_{t-1}\pi_{t+1} = \lambda G (I - \beta Q)^{-1} Q s_{t-1}$, and $E_{t-1}x_t = GQs_{t-1}$. Thus, if we think of the vector s_{t-1} as representing all the relevant instruments for the two endogenous regressors, π_{t+1} and x_t, in the policy rule, then it is clear that identification fails when s_t is a scalar. To see if this could happen under the canonical new Keynesian model, I examine what this model implies about the equilibrium dynamics of the output gap.

[8] However, if the Phillips curve contained intrinsic sources of persistence, such as indexation, backward-looking behavior, or *autocorrelated* cost-push shocks, as in Clarida, Gali, and Gertler (1999), $\lambda \neq 0$ would not be necessary for identification, since intrinsic persistence adds exogenous dynamics to inflation and hence lagged inflation can act as an instrument for the expectations of future inflation even when the Phillips curve is flat.

In line with Clarida, Galí, and Gertler (2000) and Lubik and Schorfheide (2004), I assume that the exogenous variables z_t and g_t are autoregressive of order one: $z_t = \rho_z z_{t-1} + \varepsilon_{z,t}$ and $g_t = \rho_g g_{t-1} + \varepsilon_{g,t}$, where $\varepsilon_{z,t}$ and $\varepsilon_{g,t}$ are innovations. Next, using the identity $y_t = x_t + z_t$ and the equation for z_t, the Euler equation (6) can be expressed in terms of the output gap x_t as follows:

$$x_t = E_t x_{t+1} - \sigma \left(r_t - E_t \pi_{t+1} \right) + g_t - \left(1 - \rho_z \right) z_t. \tag{10}$$

The equilibrium dynamics of π_t, x_t and r_t are now characterized by the Phillips curve (5), the output gap equation (10) and the policy rule $r_t = \psi_\pi E_t \pi_{t+1} + \psi_x x_t + \varepsilon_{r,t}$, and they depend on whether the equilibrium is determinate or indeterminate.

4.1.1 Determinacy

It is well-known that when the equilibrium is determinate, the endogenous variables are uniquely determined by the exogenous state variables z_t, g_t and the monetary policy shock $\varepsilon_{r,t}$. Specifically, substituting for r_t in equation (10) using the policy rule, the new Keynesian model can be written compactly as

$$B_0 Y_t = B_1 E_t Y_{t+1} + C X_t + C_r \varepsilon_{r,t} \tag{11}$$

where $Y_t = \left(\pi_t, x_t \right)'$, $X_t = \left(z_t, g_t \right)'$, and the coefficient matrices B_0, B_1, C, and the vector C_r are functions of the structural parameters $\beta, \lambda, \sigma, \psi_\pi, \psi_x$. When the Taylor principle is satisfied, i.e., when both roots of the characteristic polynomial $\det \left(\mu B_0 - B_1 \right) = 0$ are explosive, the equilibrium dynamics can be expressed as

$$Y_t = A X_t + A_r \varepsilon_{r,t}, \tag{12}$$

where the coefficients A and A_r are functions of the structural parameters $\beta, \lambda, \sigma, \psi_\pi, \psi_x, \rho_z$ and ρ_g.[9]

Equation (12) shows that, in equilibrium, x_t is linear in z_t, g_t and $\varepsilon_{r,t}$. So, for identification, we require that there are at least two state variables with nonzero autocorrelation that can serve as instruments. This immediately implies the necessity of $\rho_z \neq 0$ and $\rho_g \neq 0$. Moreover, note that the two persistent exogenous variables, z_t and g_t, enter the system only through the output gap equation (10). Thus, identification also requires that $\rho_z \neq 1$, i.e., potential output should not be a random walk, for otherwise, z_t would no longer be relevant. Finally, identification requires that $\rho_z \neq \rho_g$, because if that were the case, then the dynamics of x_t could be characterized by a single state variable $s_t = g_t - (1 - \rho_z) z_t$, whose transition equation could be written as $s_t = \rho_z s_{t-1} + \varphi_t$, for some innovation process φ_t, and so there would be only one relevant instrument, s_{t-1}.

The above discussion can be made rigorous by solving the model explicitly and obtaining the rank condition as a function of the structural parameters. From equation (12), it follows that $E_{t-1}(\pi_{t+1}, x_t)' = F(z_{t-1}, g_{t-1})'$ for some 2×2 matrix F which is a function of the structural parameters, and whose rank is equal to two if and only if $\lambda(\rho_z - \rho_g)(\rho_z - 1)\rho_z\rho_g \neq 0$.[10] This corresponds precisely to the conditions I outlined above.

Based on the above results, one should expect identification to become weaker when potential output is highly persistent (ρ_z close to 1), or when the persistence in the two fundamental shocks that drive the dynamics is similar (ρ_z close to ρ_g). In fact, this is true of the baseline model in the simulations of Clarida, Galí, and Gertler (2000, section IV) (they set $\rho_z = \rho_g = 0.9$), and in line with the estimates (posterior means) reported by Lubik and Schorfheide (2004) ($\rho_z = 0.85$ and $\rho_g = 0.83$ over the Volcker-Greenspan period). Hence,

[9] By the method of undetermined coefficients, it can be shown that A solves $B_0 A = B_1 A D + C$ and $A_r = B_0^{-1} C_r$, see Woodford (2003, appendix C).

[10] The proof is contained in an appendix available from the author.

both of these cases seem quite plausible.

4.1.2 Indeterminacy and sunspots

Now, I turn to the case of indeterminacy in order to show why sunspot fluctuations improve identification. When the Taylor principle is violated, the characteristic polynomial $\det(\mu B_0 - B_1) = 0$ of the model (11) has one explosive and one stable root (Woodford 2003, proposition 4.3). Let ρ_u denote the inverse of the highest (stable) root and let the corresponding eigenvector be given by A_u, which is such that $B_0 A_u = B_1 A_u \rho_u$. Following Lubik and Schorfheide (2003, 2004), the set of equilibria can be characterized by

$$\begin{aligned} Y_t &= AX_t + A_r \varepsilon_{r,t} + A_u u_t \\ u_t &= \rho_u u_{t-1} + \zeta_t, \end{aligned} \tag{13}$$

where ζ_t is an arbitrary innovation process.[11] The key difference from the determinate equilibrium (12) is that, provided $A_u \neq 0$, the endogenous variables π_t and x_t now also depend on the additional state variable u_t that is driven by sunspots. Hence, since u_t is autocorrelated, u_{t-1} provides an additional relevant instrument for inflation and the output gap in the policy rule.

Formally, equation (13) implies that $E_{t-1}(\pi_{t+1}, x_t)' = F(z_{t-1}, g_{t-1})' + F_u u_{t-1}$, where F, and F_u are functions of the structural parameters. Moreover, since the matrix F is the same function of the structural parameters under determinacy and indeterminacy, it follows that if the rank condition is satisfied under determinacy, it will also be satisfied under indeterminacy. So, the presence of non-fundamental fluctuations caused by indeterminacy

[11] To verify that this is indeed a solution to the model (11), note first that Y_t is stable, since $|\rho_u| < 1$. Then, substitute for Y_t and $E_t Y_{t+1}$ in the original model (11) to obtain $[B_0 A - B_1 A D - C]X_t + [B_0 A_u - B_1 A_u \rho_u]u_t - (B_0 A_r - C_r)\varepsilon_{r,t} = 0$, and note that A, A_r, which are as in the determinate case, ρ_u and A_u are such that the above equation is satisfied for all $X_t, \varepsilon_{r,t}$ and u_t.

improves the identification of the policy rule coefficients.[12]

It is important to emphasize that identification problems need not arise only when the equilibrium is determinate. This is because the equilibrium dynamics under indeterminacy may resemble the dynamics under determinacy. The set of indeterminate equilibria characterized by equation (13) also comprises the special case in which $A_u = 0$, which is akin to the determinate equilibrium given by equation (12). Because the equilibrium dynamics with $A_u = 0$ involve only two state variables z_t, g_t, as opposed to three state variables when $A_u \neq 0$, this special solution is referred to as the *minimal state variable* (MSV) solution (McCallum, 1983). So, identification problems may arise under indeterminacy if the equilibrium is of the MSV form. This assumption is common in applied work.

Finally, note that in their full-information analysis, Lubik and Schorfheide (2004) make use of an additional identifying restriction on the covariance between the fundamental innovations $\varepsilon_{z,t}, \varepsilon_{g,t}, \varepsilon_{r,t}$. If one assumes that the monetary policy shock, $\varepsilon_{r,t}$, is uncorrelated with the taste and technology shocks, $\varepsilon_{g,t}$ and $\varepsilon_{z,t}$, as Lubik and Schorfheide did, one can use the latter as instruments in the policy rule equation. These instruments are typically quite good, and so the policy rule parameters will be identified even when they are not identified by exclusion restrictions on the dynamics.

4.2 Implications of an increase in policy inertia

I now go back to the baseline specification of the policy rule (2) with $\rho \neq 0$. Identification of the feedback coefficients in this model will also become problematic when ρ is close to one. This situation might be called 'excess smoothing' or excess gradualism in policy reaction, because if the interest rate moves very little in response to changes in inflation and output, the resulting path of interest rates could be mistaken as evidence of policy inactivity.

[12] A similar argument was made in Lubik and Schorfheide (2004).

To shed some light on this issue, I compare the estimates of the smoothness parameter ρ over different periods. Before Volcker, ρ is estimated at 0.68 with a standard error of 0.1. It becomes 0.82 (s.e. 0.05) between 1979 and 1997, and finally, 0.92 (s.e. 0.02) over the Greenspan sample. This suggests policy has become more gradual over time, and provides an additional explanation of why the coefficients of the reaction function (1) have become less accurately estimable recently relative to the past.

One interpretation of policy inertia is that they reflect commitment to a policy that aims at stabilizing the economy in the face of persistent shocks and avoids the 'inflation bias' of discretionary policies, see Svensson and Woodford (2003). Faced with autocorrelated shocks, policy under commitment should be seen to react to past as well as current shocks. Hence, the increase in policy inertia over time may, perhaps, be indicative of an attempt by the policy makers to demonstrate commitment to such a policy. However, this comes at a cost: it makes it harder to signal that monetary policy adheres to the Taylor principle.

5 Conclusions

This study re-examined the conclusions of Clarida, Galí, and Gertler (2000), using econometric methods that are robust to potential failure of identification of the policy reaction function. My results confirm the conclusion of Clarida, Galí, and Gertler (2000) that policy before Volcker led to indeterminacy and sunspot fluctuations. However, I find that the reaction function cannot be accurately estimated using data after 1979.

I provide three explanations for this finding. The first explanation relates to possible differences in the incidence of sunspot fluctuations in the two periods. I argue that indeterminacy prior to 1979 may have induced exogenous variation in the expectations of inflation and the output gap due to sunspot fluctuations, and this, in turn helps identify the reaction function coefficients over that period. In contrast, absence of sunspot fluctuations could account for the weak identification of the reaction function after 1979.[13]

The second explanation relates to the increase in policy inertia, or the smoothing of interest rate changes over the sample. This increase makes interest rates less responsive to expected changes in inflation and the output gap, and it can be mistaken for policy inactivity.

Finally, a third explanation comes from the fact that the residual of the reaction function is much more variable in the first few years of Volcker's tenure than it is in the pre-Volcker sample. This is not surprising, in view of the fact that monetary policy over that period is best characterized as targeting money, and thus the model is not expected to provide a good fit over that period. The estimates over the Greenspan era (when residual volatility falls to pre-1979 levels) are considerably more precise, though not precise enough to rule out indeterminacy.

[13] An important caveat against this interpretation of the empirical findings is that it relies to some extent on the new Keynesian model of the transmission mechanism that was used in Clarida, Galí, and Gertler (2000). Beyer and Farmer (2007) and Lubik and Schorfheide (2004, 2007) provide a discussion of this issue.

References

Anderson, T. W. and H. Rubin (1949). Estimation of the parameters of a single equation in a complete system of stochastic equations. *Ann. Math. Statistics 20*, 46–63.

Andrews, D. W. and J. H. Stock (2005). Inference with Weak Instruments. NBER Technical Working Papers 0313, National Bureau of Economic Research, Inc.

Benati, L. (2007). Indeterminacy, the predictive content of money and the Great Moderation. mimeo, European Central Bank.

Benati, L. and P. Surico (2007). VAR analysis and the Great Moderation. mimeo, Bank of England.

Beyer, A. and R. E. A. Farmer (2007). Testing for indeterminacy: An application to U.S. Monetary Policy: Comment. *American Economic Review 97*(1), 524–529.

Canova, F. and L. Sala (2005). Back to square one: Identification issues in DSGE models. Economics Working Papers 927, Department of Economics and Business, Universitat Pompeu Fabra.

Clarida, R., J. Galí, and M. Gertler (1998). Monetary Policy Rules in Practice: Some International Evidence. *European Economic Review 42*, 1033–67.

Clarida, R., J. Gali, and M. Gertler (1999). The Science of Monetary Policy: A New Keynesian Perspective. *Journal of Economic Literature 37*(4), 1661–1707.

Clarida, R., J. Galí, and M. Gertler (2000). Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory. *Quarterly Journal of Economics 115*, 147–180.

Cochrane, J. H. (2007). Identification with Taylor Rules: A Critical Review. NBER Working Papers 13410, National Bureau of Economic Research, Inc.

Dufour, J.-M. (2003). Identification, Weak Instruments and Statistical Inference in Econometrics. *Canadian Journal of Economics 36*(4), 767–808. Presidential Address to the Canadian Economics Association.

Dufour, J.-M., L. Khalaf, and M. Kichian (2006). Inflation dynamics and the new Keynesian Phillips curve: An identification robust econometric analysis. *Journal of Economic Dynamics and Control 30*(9-10), 1707–1727.

Kleibergen, F. (2005). Testing parameters in GMM without assuming that they are identified. *Econometrica 73*(4), 1103–1123.

Kleibergen, F. and S. Mavroeidis (2008). Weak Instrument Robust Tests in GMM and the New Keynesian Phillips Curve. Mimeo, Brown University, USA.

Leeper, E. M. (1991). Equilibria under 'active' and 'passive' monetary and fiscal policies. *Journal of Monetary Economics 27*(1), 129–147.

Lubik, T. A. and F. Schorfheide (2003). Computing sunspot equilibria in linear rational expectations models. *J. Econom. Dynam. Control 28*(2), 273–285.

Lubik, T. A. and F. Schorfheide (2004). Testing for indeterminacy: An application to U.S. Monetary Policy. *American Economic Review 94*(1), 190–216.

Lubik, T. A. and F. Schorfheide (2007). Testing for indeterminacy: An application to U.S. Monetary Policy: Reply. *American Economic Review 97*(1), 530–533.

Ma, A. (2002). GMM estimation of the New Keynesian Phillips Curve. *Economics Letters 76*, 411–417.

Mavroeidis, S. (2004). Weak identification of forward-looking models in monetary economics. *Oxford Bulletin of Economics and Statistics 66*(Supplement), 609–635.

McCallum, B. T. (1983). On non-uniqueness in rational expectations models: An attempt at perspective. *Journal of Monetary Economics 11*, 139–168.

Nason, J. M. and G. W. Smith (2005). Identifying the new Keynesian Phillips curve. Working Paper 2005-01, Federal Reserve Bank of Atlanta.

Newey, W. K. and K. D. West (1987). A simple, positive semidefinite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica 55*(3), 703–708.

Orphanides, A. (2002). Monetary-Policy Rules and the Great Inflation. *American Economic Review 92*(2), 115–120.

Primiceri, G. E. (2006). Why Inflation Rose and Fell: Policymakers' Beliefs and US Postwar Stabilization Policy. *Quarterly Journal of Economics 121*(3), 867–901.

Sargent, T. (1999). *The conquest of American inflation.* USA: Princeton University Press.

Sims, C. A. and T. Zha (2006). Were There Regime Switches in U.S. Monetary Policy? *American Economic Review 96*(1), 54–81.

Stock, J. H. and J. H. Wright (2000). GMM with weak identification. *Econometrica 68*(5), 1055–1096.

Stock, J. H., J. H. Wright, and M. Yogo (2002). GMM, weak instruments, and weak identification. *Journal of Business and Economic Statistics 20*, 518–530.

Svensson, L. E. O. and M. Woodford (2003, June). Implementing optimal policy through inflation-forecast targeting. NBER Working Papers 9747, National Bureau of Economic Research, Inc.

Taylor, J. B. (1993). Discretion versus policy rule in practice. *Carnegie–Rochester Conference Series on Public Policy 39*, 195–214.

Woodford, M. (2003). *Interest and Prices: Foundations of a Theory of Monetary Policy.* Princeton University Press.