Testing for indeterminacy in U.S. monetary policy*

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Abstract

We revisit the question of indeterminacy in U.S. monetary policy using identification-robust methods. We 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 because confidence sets are very large. We 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 too gradual or excessively smooth recently. All in all, our analysis 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

JEL: C22, E31

1 Introduction

In a seminal paper, Clarida, Galí, and Gertler (2000) studied the implications of monetary policy for macro-economic 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 this equation 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-Greespan era was found to satisfy the Taylor principle, and this was seen as an important factor contributing to the conquest of US inflation.

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. Sims and Zha (2006) emphasized regime switching in volatility, rather than the parameters of the reaction function. This list is by no means exhaustive.

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) and Mavroeidis (2004). Lubik and Schorfheide (2004) also studied this problem from a Bayesian perspective using a full-information approach. In this paper, we follow closely the limited information approach of Clarida, Galí, and Gertler (2000), which makes minimal assumptions about the nature of macroeconomic dynamics.[1] The key difference is that we use the statistical methods proposed by Stock and Wright (2000) and Kleibergen (2005), which are robust to identification failure, see Stock, Wright, and Yogo (2002) or Andrews and Stock (2005) for reviews.

The results of this paper can be summarized as follows.

We find that the conclusion that policy reaction did not satisfy the conditions for determinacy (the Taylor principle) 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.

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[1] We use an identification-robust full-information approach in a related study, see Mavroeidis (2007)

We then argue that these apparently pessimistic 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 predictability in inflation and output to identify the policy rule. In contrast, the weak identifiability over the Volcker-Greenspan sample could well be a consequence of appropriate policy reaction, though it is not possible to distinguish between this and alternative explanations. Thus, our analysis points out the limitations of this limited information approach, and the need to make use of further identifying restrictions 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).

The paper also provides results for the full Greenspan sample. The coefficients in the reaction function are not sufficiently accurately estimable over that period to rule out the possibility of indeterminacy. There is another possible explanation for this finding. 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. We 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 in 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. Secondly, even if confidence sets turn out to be large, they can still be highly informative and admit interesting and useful economic interpretations.

2   The model

2.1   Monetary policy rules

We consider policy rules of the type proposed by Clarida, Galí, and Gertler (2000):

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

where r_t^* denotes the target nominal policy rate at time t, $\pi_{t,k}$ denotes average (annualized) inflation between periods t and $t+k$ and similarly for the output gap $x_{t,q}$.[2] 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, we 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 (1) according to

$$\rho(L) r_t = \rho(1) r_t^* + \varepsilon_{r,t}, \tag{2}$$

where $\rho(L)$ is a lag polynomial of order p, 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., $E_{t-1}\varepsilon_{r,t} = 0$.

The baseline specification in Clarida, Galí, and Gertler (2000) is $k = q = 1$. Given their timing assumptions, this can be written as

$$\rho(L) r_t = \alpha + \rho(1) E_t (\psi_\pi \pi_{t+1} + \psi_x x_t) + \varepsilon_{r,t}. \tag{3}$$

where $\alpha = \rho(1)(r^* - \psi_\pi \pi^*)$. For $\rho(L) = 1 - \rho L$, this equation coincides with the model discussed extensively in Woodford (2003, chapter 4). Replacing expectations by realizations, Eq. (3) can be written as

$$\rho(L) r_t = \alpha + \rho(1)(\psi_\pi \pi_{t+1} + \psi_x x_t) + e_t, \tag{4}$$

$$e_t = \varepsilon_{r,t} - \rho(1)[\psi_\pi(\pi_{t+1} - E_t\pi_{t+1}) + \psi_x(x_t - E_tx_t)]. \tag{5}$$

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.

2.2 The transmission mechanism

To discuss the implications of the monetary policy rule (3) for macroeconomic fluctuations, we need a model of the monetary transmission mechanism. For this purpose, we 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

$$\pi_t = \beta E(\pi_{t+1}|\Omega_t) + \lambda(y_t - z_t) \tag{6}$$

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[2] We maintain exactly the same timing assumption for output gap as in Clarida, Galí, and Gertler (2000, footnote 5).

$$y_t = E\left(y_{t+1}|\Omega_t\right) - \sigma\left[r_t - E\left(\pi_{t+1}|\Omega_t\right)\right] + g_t \tag{7}$$

Equation (6) 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 (7) 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 capture 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) (uninteresting constants relating to the inflation target and the long-run equilibrium real rate have been omitted).

The model consisting of Equations (6), (7), (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 (2003, Proposition 4.6) shows that a necessary condition for determinacy in this model is given by

$$\psi_\pi + \frac{1-\beta}{\lambda}\psi_x - 1 \geq 0. \tag{8}$$

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. Determinacy also requires that the response to inflation is not too large, see Woodford (2003). It turns out that this additional condition is not empirically binding, so we do not discuss it here.

3 Inference on indeterminacy

3.1 The story of Clarida Gali and Gertler

Clarida, Galí, and Gertler (2000) estimated the policy rule (3) using quarterly data from 1960 to 1997. They estimated the parameters over various subsamples, and checked the condition for determinacy (8). This requires knowledge of the parameters of the Phillips curve (6) 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.

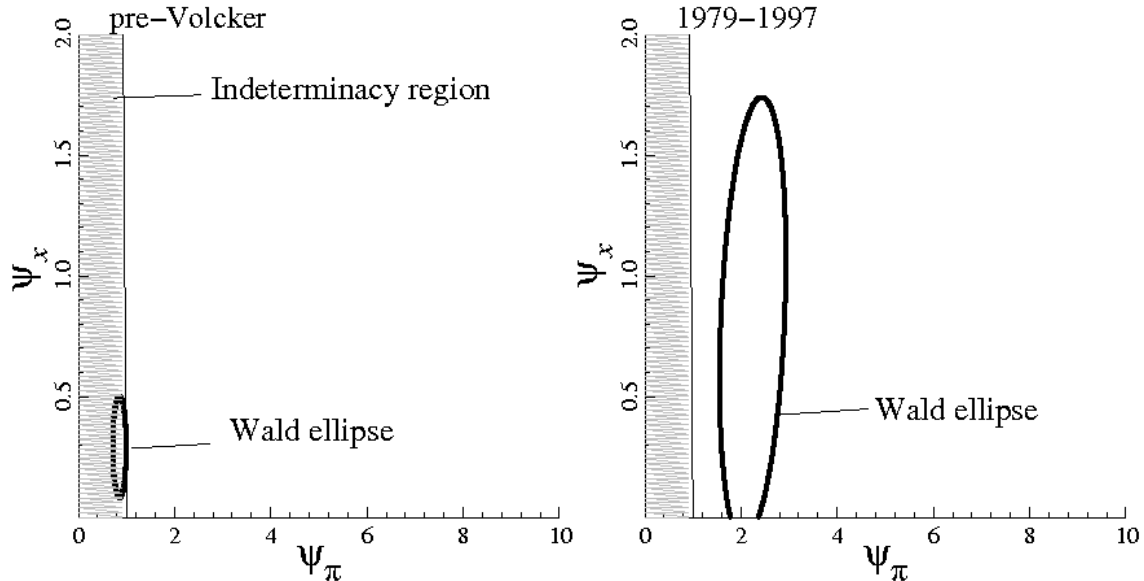Figure 1: 90% level Wald confidence sets for the parameters of the Taylor rule $\rho\left(L\right) r_t = c + \rho\left(1\right)\left(\psi_\pi E_t \pi_{t+1} + \psi_x E_t x_t\right) + \varepsilon_t$. The model is estimated by GMM using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix. The pre-Volcker sample is 1961:q1 to 1979:q2.

This conclusion can be shown more formally by constructing two-dimensional confidence sets on the parameters $\left(\psi_\pi, \psi_x\right)$. We use the same data and methods as Clarida, Galí, and Gertler (2000). Figure 1 presents the 90% level confidence ellipses based on inverting the Wald test on $\left(\psi_\pi, \psi_x\right)$ over the two key subsamples that they studied. This picture is truly remarkable. 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 has been passive and 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 undeniable evidence that policy over that period satisfied the Taylor principle (8).

However, it is by now well-known that DSGE models may suffer from weak identification and thus results based on conventional GMM tests could be very misleading, see, e.g., Mavroeidis (2004) and Canova and Sala (2005). Therefore, it is important to re-examine those conclusions using identification-robust methods.
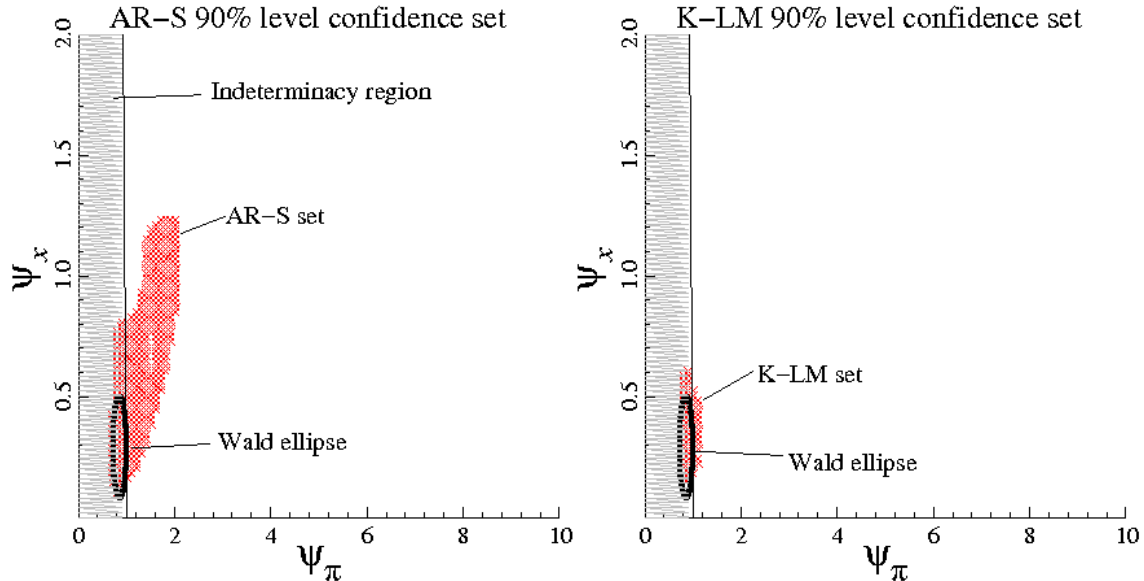
Figure 2: 90% level confidence sets for the parameters of the Taylor rule $r_t = c + \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1 - \rho_1 - \rho_2) E_t (\psi_\pi \pi_{t+1} + \psi_x x_t) + \varepsilon_t$. The model is estimated by GMM over the period 1961:q1 to 1979:q2, using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix.

3.2 Identification-robust tests of indeterminacy

Figure 2 presents 90% level confidence sets for the policy rule parameters (ψ_π, ψ_x) based on inverting the Anderson-Rubin (AR-S) statistic of Stock and Wright (2000) (left-hand panel) and the conditional score (K-LM) statistic of Kleibergen (2005) (right-hand panel).[3] The Wald ellipse is superimposed for comparison. We notice that the AR-S region is considerably wider than the Wald ellipse, and cuts across to the determinacy region. However, this need not imply any identification problems, and may simply be a consequence of the fact that the AR-S test is less powerful than the Wald test when the instruments are good and the model is over-identified (the degree of over-identification is 8 in this case).

In contrast, the K-LM test has the same degrees of freedom as the Wald test and does not suffer a loss of power relative to the Wald test when the parameters are well-identified, see Kleibergen (2005). The 90% level set based on inverting the K-LM statistic in the right-hand panel of figure 2 is actually very similar to the Wald confidence ellipse. This can be interpreted as evidence that the parameters of the model are

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[3] The K-LM confidence set reported here is actually based on the combination of a 9% level KLM and a 1% JKLM test, as suggested by Kleibergen (2005). This is a device that improves the power of the KLM test against irrelevant alternatives at which the overidentifying restrictions are violated (that's when JKLM has power).
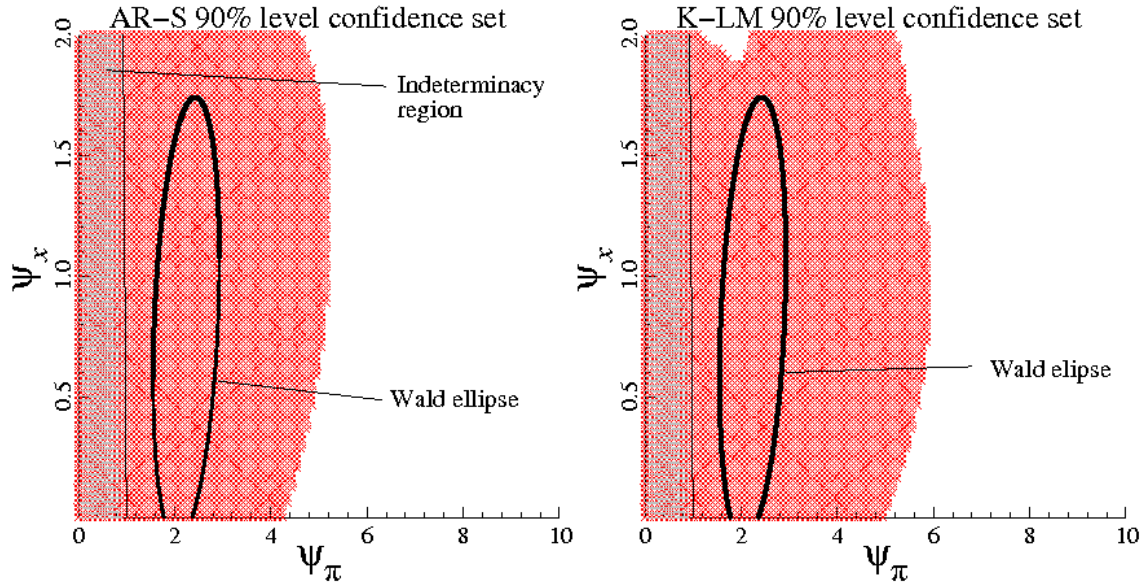
Figure 3: 90% level confidence sets for the parameters of the Taylor rule $r_t = c + \rho r_{t-1} + (1-\rho) E_t (\psi_\pi \pi_{t+1} + \psi_x x_t) + \varepsilon_t$. The model is estimated by GMM over the period 1979:q3 to 1997:q4, using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix.

well-identified. Thus, the earlier finding that monetary policy before Volcker violated the Taylor principle appears to be robust to the quality of the instruments.

Let us now look at the Volcker-Greenspan period. Figure 3 presents the identification robust 90% level AR-S and K-LM confidence sets for the parameters of the reaction function (ψ_π, ψ_x) over 1979-1997. The identification-robust confidence sets now stand 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 true degree of uncertainty about the parameters. Even the K-LM set is much wider than the Wald ellipse, indicating that the parameters are not well-identified.

3.3   Economic interpretation of the results

An initial reading of Figure 3 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. On the face of it, this is a rather pessimistic conclusion.

However, upon further reflection, one realizes that there is a great deal to be learned from these results.

The key to this realization lies in the very source of weak identification, which is directly linked to the question of determinacy. As we 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 effect shocks on future inflation and output. As a result, these variables become less predictable than they would otherwise be. This interpretation of Figures 2 and 3 is very much in line with the view that policy pre-Volcker destabilized expectations. This, in turn, provided sufficient predictability 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 we are 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. Simulations reported in section 5 add further weight to this conclusion.

It is important not to read too much into this interpretation of the empirical results, however. It should be noted that weak identification is not solely a consequence of determinacy. It may also arise when the equilibrium is indeterminate but for some other reason sunspot fluctuations do not play an important role (as a special case, think of the 'sunspot-free' Minimum State Variable solution of McCallum (1983)). In other words, stability of expectations may be conceivably achieved by methods other than active response to inflation. The model we study here is too simple to address the issues relating to the evolution of expectations, and the question of whether 'actions speak louder than words'. Models that incorporate learning, as in Primiceri (2006) or Milani (2005) seem more appropriate to study those issues.

3.4   Results for the Greenspan era

It is well-known that monetary policy over much of Volcker's tenure has been designed to control money, rather than interest rates. This led to significant volatility in the policy rate, which is reflected in the standard deviation of the residuals in the policy rule over that period, see the left panel of Figure 5. Moreover, the beginning of the 1980s was a period of sharp disinflation. It is therefore interesting to see how the forward-looking Taylor rule (3) characterizes monetary policy under the more stable Greenspan era.

Figure 4 presents confidence sets on the policy rule parameters (ψ_π, ψ_x) based on inverting the Anderson-Rubin (AR-S) statistic (left-hand panel) and the conditional score (K-LM) (right-hand panel), as well as the non-robust Wald test. One key difference with the results for the period 1979-1997 given in Figure 3 is that all three confidence sets are now smaller. To a large extent, this can be explained by the large fall in
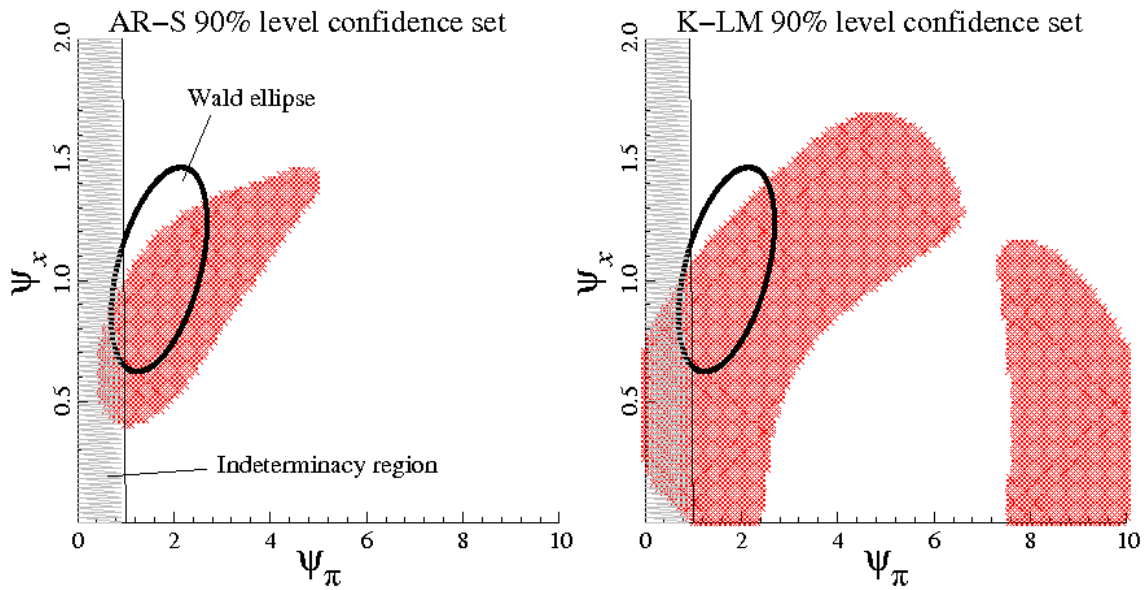
Figure 4: The reaction function under Greenspan. 90% level confidence sets for the parameters of the Taylor rule $r_t = c + \rho_1 r_{t-1} + \rho_2 r_{t-2} + (1 - \rho_1 - \rho_2) E_t (\psi_\pi \pi_{t+1} + \psi_x x_t) + \varepsilon_t$. The model is estimated by GMM over the Greenspan era (1997 to 2006), using four lags of π_t, x_t and r_t as instruments, and Newey-West weight matrix.
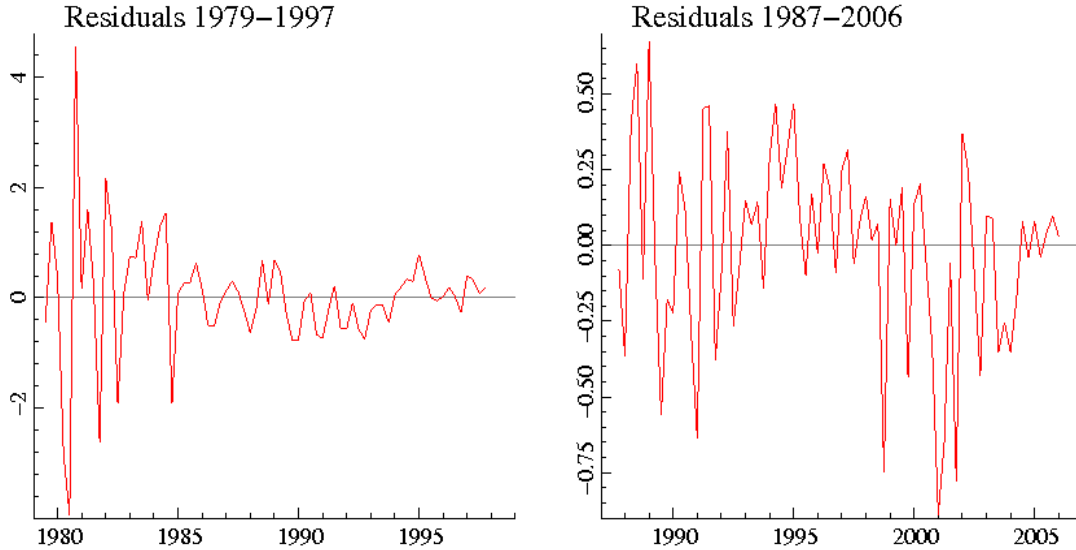
Figure 5: Residuals of the policy rule: $\hat{e}_t = \hat{\rho}(L) r_t - \hat{c} - \hat{\rho}(1) \left[\hat{\psi}_\pi \pi_{t+1} + \hat{\psi}_x x_t \right]$. The parameters are estimated by GMM over the two periods: 1979:q3-1997:q4 and 1987:q1-2006:q1.

the variability of the residual e_t in the policy rule regression (4), see Figure 5. 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, see Eq. (5). Thus, this drop in volatility could arise from different sources. Even though the parameters of the model (3) are more accurately estimable over the Greenspan era, problems with the identifiability of ψ are still evident in the confidence sets reported in Figure 4. Even though the point estimates lie in the determinacy region, all three confidence sets include values in the indeterminacy region.

4 Discussion of identification

In this section, we elaborate further into the possible explanations of the empirical results presented above.

There are at least two sources of identification problems for the parameters of the policy rule (3). One is when inflation and/or the output gap are not forecastable by information available at time $t-1$. The other arises when the smoothing parameter $\rho(1)$ in the reaction function (2) is close to 0, or, in other words, the adjustment to the target rate (1) is too slow.

4.1 The implications of determinacy

Formally, the model will be partially identified whenever a linear combination of the endogenous variables, inflation and the gap, is completely uncorrelated with the lagged variables beyond the lags of r_t which appear in the model as exogenous regressors. We can check this by looking at the reduced form for π_t and x_t that is implied by the model (6), (7) and (3).

Lubik and Schorfheide (2004) characterize the full set of stable solutions of this model, building on the approach of Sims (2002). Suppose that the exogenous processes z_t and g_t evolve according to

$$z_t = \rho_z z_{t-1} + \varepsilon_{z,t}$$

$$g_t = \rho_g g_{t-1} + \varepsilon_{g,t}$$

where $\varepsilon_{z,t}$ and $\varepsilon_{g,t}$ are innovation processes. The model can then be written in the Sims (2002) canonical form:

$$\Gamma_0 s_t = \Gamma_1 s_{t-1} + \Psi \varepsilon_t + \Pi \eta_t \tag{9}$$

where s_t is a vector of state variables $s_t = (E_t \pi_{t+1}, E_t y_{t+1}, \pi_t, y_t, r_t, \ldots, r_{t-p+1}, z_t, g_t)'$, p is the order of the $\rho(L)$ polynomial in the rule (3), $\varepsilon_t = (\varepsilon_{z,t}, \varepsilon_{g,t}, \varepsilon_{r,t})'$ are exogenous, and $\eta_t = (\eta_{\pi,t}, \eta_{x,t})'$ are the one-step-ahead forecast errors in π_t and y_t, $\eta_{\pi,t} = \pi_t - E_{t-1} \pi_t$ and $\eta_{y,t} = y_t - E_{t-1} y_t$. The matrices $\Gamma_0, \Gamma_1, \Gamma_u$ and Π are sparse and depend on the parameters θ, containing $\beta, \lambda, \sigma, \psi_\pi, \psi_x, \rho_z, \rho_g$ and $\rho_i, i = 1, \ldots, p$.

The full set of solutions takes the form, see Lubik and Schorfheide (2003),

$$s_t = \Gamma_1^*(\theta) s_{t-1} + \Gamma_\varepsilon^*(\theta) \varepsilon_t + \Gamma_\zeta(\theta) [(M^*(\theta) + M) \varepsilon_t + \zeta_t] \tag{10}$$

given s_0 and an arbitrary martingale difference process ζ_t, which is referred to as a sunspot shock. The dimension of ζ_t depends on the degree of indeterminacy r (which is at most 1 here), and the matrix $\Gamma_\zeta(\theta)$ is restricted to lie in a particular r-dimensional linear subspace. M is an arbitrary $r \times 3$ matrix, while $M^*(\theta)$ is a $r \times 3$ matrix specified as in Lubik and Schorfheide (2004, Eq. 30) to make the impulse responses continuous on the boundary of the determinacy region.

When the equilibrium is determinate, $r = 0$ and the last two terms in the solution (10) drop out. In fact, it can be shown (e.g., using the method of undetermined coefficients) that the determinate solution implies the following restricted reduced form dynamics in π_t and x_t (see, e.g., Mavroeidis (2004) for a special case of this)

$$\begin{pmatrix} \pi_t \\ x_t \end{pmatrix} = \sum_{i=1}^{p} b_i(\theta) r_{t-i} + C(\theta) \begin{pmatrix} z_t \\ g_t \end{pmatrix} + d(\theta) \varepsilon_{r,t}, \tag{11}$$

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where p is the order of the $\rho(L)$ polynomial in (3). It is immediately obvious that if the forcing variables z_t and g_t are serially independent, then the optimal predictors of π_t and x_t are the lags of r_t that already appear in the Taylor rule (3) as exogenous regressors. Therefore, Eq. (3) will not be identifiable using lags of the variables as instruments.[4]

The situation that z_t and g_t are serially uncorrelated seems unrealistic, since it is well-known that inflation and the output gap have strong autoregressive dynamics in the US. However, identification problems may still arise if there exists a linear combination of π_{t+1} and x_t that is poorly forecastable by past information, as explained in Mavroeidis (2004). In fact, such a situation will arise in the present model whenever ρ_z is close to ρ_g. This is indeed 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). To further demonstrate that point, we report in the following section simulations of the model under indeterminacy and determinacy based on the parameter estimates reported by Lubik and Schorfheide (2004, Table 3).

It is important to point out that such identification problems need not arise only when the equilibrium is determinate. A solution of the form (11) may also arise as a special case of the general solution (10), even if the conditions for determinacy are not satisfied. One example is the minimum state variable solution of McCallum (1983), which also takes the form (11).

Finally, the indeterminate solution (10) can be written as an infinite-order vector autoregressive process (provided $M \neq 0$ and/or $\sigma_\zeta \neq 0$). Thus, π_t and x_t may be predictable even in the special case in which z_t and g_t are serially uncorrelated, so the model could be identified even in this case. The simulations reported in section 5 demonstrate this point clearly. Having said that, it is not, in general, possible to characterize the rank condition for identification analytically, and the restrictions that it imposes on the structural parameters as well as the nature of the sunspot shocks ζ_t. That is why it is important to use inference procedures that do not rely on the validity of the identification assumption.

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[4] This fact was put forward by Lubik and Schorfheide (2004) as an argument for using a full-information approach that exploits the additional assumption that the shocks $\varepsilon_{z,t}, \varepsilon_{g,t}$ and $\varepsilon_{r,t}$ should be mutually uncorrelated. Such covariance restrictions can be a very powerful source of identification. We investigate their implications using an identification-robust method in Mavroeidis (2007).

4.2   Excess smoothing

Identification of ψ in (3) will also become problematic when $\rho(1)$ is close to 0, a situation which might be called 'excess smoothing' or excess gradualism in policy reaction. Indeed, if policy is so gradual that the interest rate moves little in response to changes in inflation and output, the resulting path of interest rates could be mistaken as evidence of policy inactivity.

In principle, one could consider testing the null hypothesis that $\rho(1) = 0$ in Eq. (3), but this raises a couple of econometric issues. First, under the null hypothesis, the parameters ψ in the Taylor rule are unidentified. This belongs to the class of problems when a nuisance parameter (here ψ) is not identified under the null. Andrews and Ploberger (1994) and Hansen (1996) showed that the asymptotic distribution of the usual test statistics is non-standard, and derived optimal tests for such hypothesis under stationarity and weak dependence restrictions. Optimality, however, is a secondary consideration here relative to the fact that, under the null hypothesis, the interest rate becomes a unit root process.

One could test the null hypothesis $\rho(1) = 0$ by standard unit root tests. The null hypothesis of a unit root cannot be rejected at conventional significance levels over the subperiods 1979-1997 and 1987-2006, though it can be rejected over 1960-1979 and over the entire sample. However, we do not wish to take such results at face value, as they would imply that the policy rate follows an autonomous stochastic trend, which is clearly an implausible description of recent US monetary policy. It is more informative to just look at the point estimates of the smoothness parameter $\rho = 1 - \rho(1)$ over time. Before Volcker, ρ is 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, which would certainly help explain, partly, why the coefficients on 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 is adheres to the Taylor principle.

5 Simulations

To illustrate further our conclusion on identification, we report simulations of the model under the two regimes of indeterminacy and determinacy. The parameters of the model are set to the estimates reported in Lubik and Schorfheide (2004, Table 3).[5] The shocks $\varepsilon_{z,t}, \varepsilon_{g,t}, \varepsilon_{r,t}$ and the sunspot shock ζ_t (where needed) are drawn from a normal distribution, with $var(\varepsilon_{z,t}) = \sigma_z^2$, $cov(\varepsilon_{z,t}, \varepsilon_{g,t}) = \sigma_{zg}$, $var(\varepsilon_{g,t}) = \sigma_g^2$, $var(\varepsilon_{z,t}) = \sigma_r^2$, $var(\zeta_t) = \sigma_\zeta^2$ and $cov(\varepsilon_{r,t}, \varepsilon_{z,t}) = cov(\varepsilon_{r,t}, \varepsilon_{g,t}) = cov(\varepsilon_{r,t}, \zeta_t) = cov(\zeta_t, \varepsilon_{z,t}) = cov(\zeta_t, \varepsilon_{g,t}) = 0$. We consider tests of restrictions on ψ_π, instead of joint restrictions on ψ_π and ψ_x purely for the sake of clarity. We simulate data from the model under the two regimes and report the rejection frequencies of various tests for a range of different values of ψ_π^0. Note that these are *not* conventional power curves (the latter are the rejection frequencies for a *given* ψ_π^0 at different true values of ψ_π). Instead, they show how likely it is to reject hypotheses on ψ_π that are far from the truth (in the simulations).[6]

We report the rejection frequencies of the following tests at the 5% level of significance: two Wald tests, based on the conventional 2-step GMM estimator used in Clarida, Galí, and Gertler (2000) (W-2STEP) as well as on the continuously updated GMM estimator (W-CUE) of Hansen, Heaton, and Yaron (1996), the AR-S, and the K-LM test.[7].

Figure 6 reports the results of the simulation that is based on the indeterminacy regime [parameters are taken from Lubik and Schorfheide (2004, Table 3, prior 2)]. It is clear that the parameter ψ_π is well-identified, since all four tests have power when the hypothesized value is away from the truth. Moreover, the rejection frequency when the null is true is equal to the nominal 5% level of the test (the Wald tests overreject, but only slightly). This is a further indication that identification is good. This picture is consistent with the tight confidence sets reported in figure 2 above, and with the conclusion reached earlier that the policy rule is identified under indeterminacy.

Next, we simulate the model under the determinacy regime. The results are reported in figure 7. The contrast with the previous figure could not have been sharper. The identification-robust tests AR-S and

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[5] In the case of indeterminacy, they report two sets of estimates, based on two different (informative) priors about sunspot dynamics. We report here only results based on the second prior, which sets $M = 0$ in the solution (10). This case makes identification stronger and provides a sharper contrast between the two periods, consistently with the empirical evidence of given earlier.

[6] We could make our point about the lack of power at distant alternatives when identification is weak using conventional power curves. We feel the alternative we use here is more intuitive, but we wish to emphasize that it makes no difference to the argument.

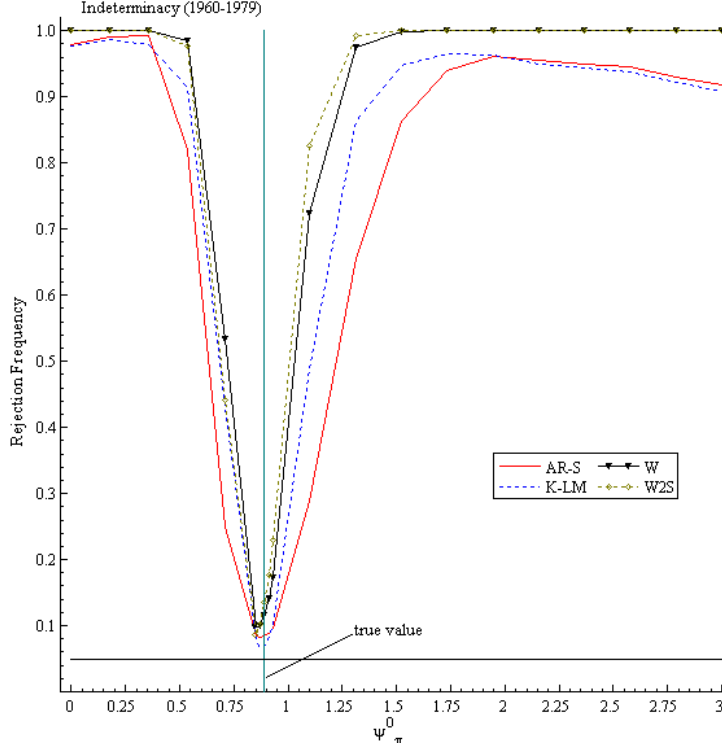[7] This is actually the combined 4% KLM, 1% JKLM test, see footnote 3

Figure 6: Rejection frequencies under indeterminacy of 5% level tests of $H_0 : \psi_\pi = \psi_\pi^0$, for different values of ψ_π^0 (the true value is fixed at $\bar{\psi}_\pi$). Estimation method is GMM with 4 lags of π_t, x_t and r_t as instruments and Newey-West (1987) covariance matrix. Reported are Wald (W-CUE and W-2STEP), AR-S (Stock-Wright, 2000) and K-LM (Kleibergen 2005). True parameters for the simulation are set to Lubik-Schorfheide (2004) estimates from pre-1979 sample: $\beta = 0.99$, $\lambda = 0.75$, $\sigma = 1/2$, $\bar{\psi}_\pi = 0.89$, $\psi_x = 0.15$, $\rho_z = 0.62$, $\rho_g = 0.85$ $M = (0, 0, 0)$ $\sigma_z = 1.16$, $\sigma_{zg} = 0.24$, $\sigma_g = 0.21$, $\sigma_r = 0.24$, $\sigma_\zeta^2 = 0.28$, $\pi^* = 3.98$ $r^* = 1.11$. $T = 500$ and number of replications is 2500.

K-LM have virtually no power even when the null is very far from the true value (and especially when it is less than 1, showing that we cannot reject indeterminacy). This is another way of showing that the model is very poorly identified over the Volcker-Greenspan period, in line with the empirical confidence sets reported in Figure 3 above. Moreover, the Wald tests, which are not robust to identification failure, are massively over-sized: they reject the true value of $\bar{\psi}_\pi = 2.19$ over 60% and 90% of the time for the CUE and 2-step GMM, respectively. This is yet another illustration of how unreliable they can be when identification fails.

Finally, to underscore the point that lack of identification *does not* necessarily imply that the equilibrium is determinate, we simulate the post-1982 regime but leaving the policy rule parameters to their estimated values pre-1979, $\psi_\pi = 0.89, \psi_x = 0.15$. We also assume *no sunspot dynamics*, i.e., $M = 0$ and $\sigma_\zeta = 0$ in (10). This is the key difference from the simulations under the indeterminacy regime that were reported earlier in Figure 6. This picture looks remarkably similar to Figure 8 and this fact further corroborates the conclusion of weak-identification in the Volcker-Greenspan period. Moreover, it is clear from this picture that lack of identification can arise even under indeterminacy. A key to this is absence of sunspot dynamics. Repeating the experiment with the addition of a sunspot shock ζ_t makes the results very similar to Figure 6 – i.e., sunspot dynamics induce identification (pictures available on request).

6   Conclusions

We 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. Our results confirm the conclusion of Clarida, Galí, and Gertler (2000) that policy before Volcker lead to indeterminacy and sunspot fluctuations. However, we find that the reaction function cannot be accurately estimated using data after 1979.

We provide three explanations for this finding. The first explanation is that determinacy potentially leads to shorter fluctuations of inflation and the output gap, thus making them less forecastable from past data. Such predictability is essential for the identification of the reaction function using the limited information method of Clarida, Galí, and Gertler (2000), which uses lags of the data as instruments.

The second explanation is the increase in policy inertia, or the smoothing of interest rate changes. Excess smoothing makes interest rates less responsive to changes in inflation and output, and can be confused with a passive policy. One view of policy inertia is that they reflect commitment to a stabilizing policy which avoids the inflation bias of discretionary policies, see Svensson and Woodford (2003). It seems that too much smoothing may hinter the ability of the monetary authority to signal their adherence to Taylor principle.
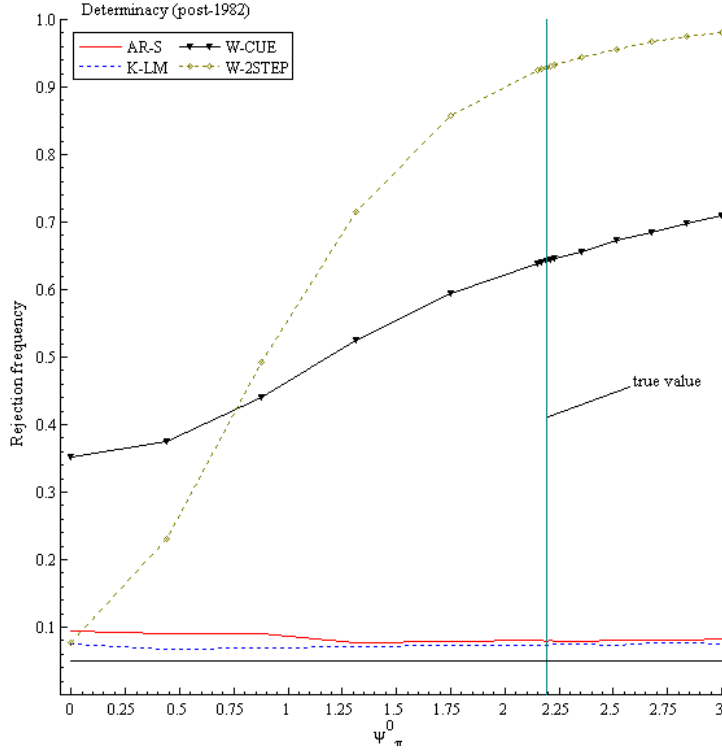
Figure 7: Rejection frequencies, under determinacy, of 5% level tests of $H_0 : \psi_\pi = \psi_\pi^0$, for different values of ψ_π^0 (the true value is fixed at $\bar{\psi}_\pi$). Estimation method is GMM with 4 lags of π_t, x_t and r_t as instruments and Newey-West covariance matrix. Reported are Wald (W-CUE and W-2STEP), AR-S (Stock-Wright, 2000) and K-LM (Kleibergen 2005). True parameters for the simulation are set to Lubik-Schorfheide (2004) estimates from post-1982 sample: $\beta = 0.99$, $\lambda = 0.58$, $\sigma = 0.54$, $\bar{\psi}_\pi = 2.19$, $\psi_x = 0.3$, $\rho_z = 0.85$, $\rho_g = 0.83$ $\sigma_z = 0.64$, $\sigma_{zg} = 0.03$, $\sigma_g = 0.18$, $\sigma_r = 0.18$, $\pi^* = 3.43$ $r^* = 3.01$. $T = 500$ and number of replications is 2500.
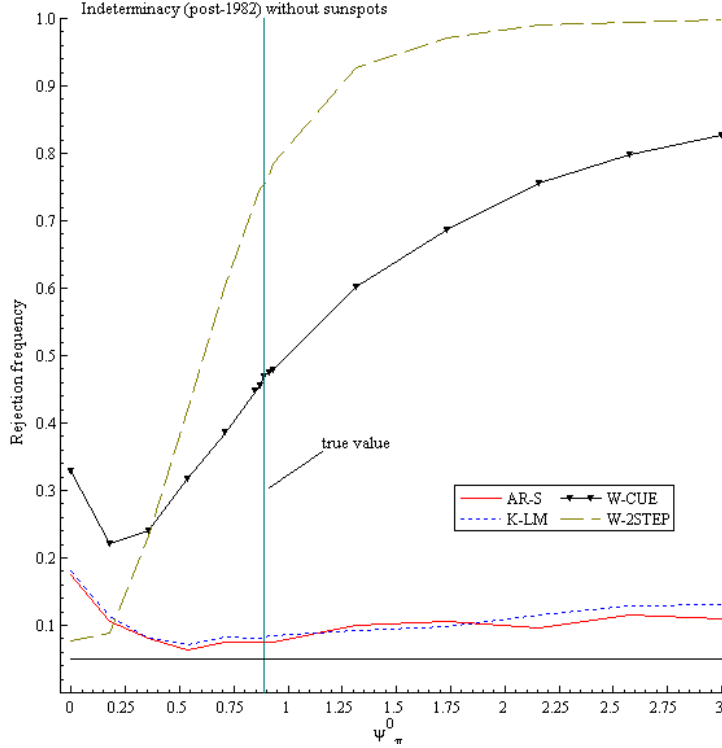
Figure 8: Rejection frequencies, under 'counterfactual' indeterminacy for post-1982, of 5% level tests of $H_0 : \psi_\pi = \psi_\pi^0$, for different values of ψ_π^0 (the true value is fixed at $\bar{\psi}_\pi$). Estimation method is GMM with 4 lags of π_t, x_t and r_t as instruments and Newey-West covariance matrix. Reported are Wald (W-CUE and W-2STEP), AR-S (Stock-Wright, 2000) and K-LM (Kleibergen 2005). True parameters for the simulation are set to Lubik-Schorfheide (2004) estimates from post-1982 sample, except for $\bar{\psi}_\pi, \psi_x$ which are set to the pre-1979 estimates:: $\beta = 0.99$, $\lambda = 0.58$, $\sigma = 0.54$, $\bar{\psi}_\pi = 0.89$, $\psi_x = 0.15$, $\rho_z = 0.85$, $\rho_g = 0.83$ $\sigma_z = 0.64$, $\sigma_{zg} = 0.03$, $\sigma_g = 0.18$, $\sigma_r = 0.18$, $\pi^* = 3.43$ $r^* = 3.01$. $T = 500$ and number of replications is 2500.

A third explanation comes from the fact that the residual in the reaction function is much more variable in the post-1979 sample than in the pre-1979 sample. Specifically, volatility of the residuals is particularly high over the first few years of Volcker's tenure. 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.

One way of dealing with the identification problem is to impose further restrictions. This was done by Lubik and Schorfheide (2004) using a full-information approach. By imposing more structure (specifically, orthogonality of the monetary policy shock to other shocks), more information can be gained at the cost of losing robustness to mis-specification of the rest of the model. In a follow-up paper we investigate the implications of imposing those restrictions for the identification of the reaction function over the Greenspan period, see Mavroeidis (2007). We do so by developing a GMM-based method that can make use of those additional restrictions without requiring any assumptions about identification (unlike the standard maximum likelihood method, which does). An additional benefit of our proposed method relative to full information maximum likelihood is that it is more transparent regarding the informational content of different types of restrictions. It turns out that covariance restrictions are an extremely powerful source of information in this model.

References

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

Andrews, D. W. K. and W. Ploberger (1994). Optimal tests when a nuisance parameter is present only under the alternative. *Econometrica 62*(6), 1383–1414.

Canova, F. and L. Sala (2005, May). 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 (2000). Monetary policy rules and macroeconomic stability: Evidence and some theory. *Quarterly Journal of Economics 115*, 147–180.

Hansen, B. E. (1996). Inference when a nuisance parameter is not identified under the null hypothesis. *Econometrica 64*(2), 413–430.

Hansen, L. P., J. Heaton, and A. Yaron (1996). Finite sample properties of some alternative GMM estimators. *Journal of Business and Economic Statistics 14*, 262–280.

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

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.

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

Mavroeidis, S. (2007). Testing for indeterminacy in U.S. monetary policy ii: a full-information approach. mimeo, Brown University.

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

Milani, F. (2005, August). Expectations, learning and macroeconomic persistence. Working Papers 050608, University of California-Irvine, Department of Economics.

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. (2002). Solving linear rational expectations models. *Computational Economics 20*(1), 1–20.

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

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

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.