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Monetary policy shifts and inflation dynamics

Paolo Surico

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*Paolo Surico**

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* Bank of England and University of Bari.
Email: paolo.surico@bankofengland.co.uk.

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Abstract

The New Keynesian Phillips Curve plays a central role in modern macroeconomic theory. A vast empirical literature has estimated this structural relationship over various post-war full samples. While it is well known that in a standard sticky price model a 'weak' central bank response to inflation generates sunspot fluctuations, the consequences of pooling observations from different monetary policy regimes for (i) *the estimates of the structural Phillips curve* and (ii) *the estimates of inflation persistence* had not been investigated. Using Monte Carlo simulations from a purely forward-looking model, this paper shows that indeterminacy can introduce a sizable persistence in the process of inflation. On the reduced form, our results show that inflation persistence can be *endogenous* to the policy regime rather than intrinsic to the structure of the economy. On the structural form, we find that by neglecting equilibrium indeterminacy the estimates of the forward-looking term of the New Keynesian Phillips Curve are biased downward. The implications are in line with the empirical evidence for the United Kingdom and United States.

Key words: Indeterminacy, New Keynesian Phillips Curve, Monte Carlo, bias, persistence.

JEL classification: E58, E31, E32.

Summary

Several researchers working on the macroeconomics of inflation have recently suggested that inflation persistence - the tendency for inflation to change only sluggishly - was very apparent in the past, but is now much reduced or absent. In the United States, the high-persistence period was in the 1970s, while for the United Kingdom it was before 1992. There is independent evidence that these periods were ones where monetary policy was relatively weak in the response to inflation.

This paper investigates the relationship between the monetary policy regime (and in particular the way in which interest rates respond to inflation) and the properties of the inflation process through the lens of the New Keynesian Phillips Curve (NKPC). Specifically, we ask what are the consequences of pooling observations from different policy regimes for the estimates of the NKPC and for the estimates of the reduced-form process of inflation (ie a backward-looking specification). This is an important policy issue, because the degree of persistence of inflation at the Phillips curve level has an impact on the appropriate monetary policy reaction. It is crucial for policymakers to know how important this is.

Using artificial data simulated from a sticky price model, this paper shows that the estimates of a NKPC featuring both forward and backward-looking components are severely biased downward when two conditions are met. First, the data are generated under a passive monetary policy regime, which is a regime where the nominal interest rate is not moved sufficiently in response to movements in inflation. Second, the empirical analysis, as is the case for the estimates currently available in the literature, neglects the possibility of a passive policy regime and hence implicitly limits the solution of the model to the case in which monetary policy is active. In the passive monetary policy case, the hypothesis of no backward-looking component is strongly rejected in spite of the fact that the data generating process does not exhibit any exogenous or endogenous persistence. The slope of the Phillips curve takes a value that is not statistically different from zero. Moreover, the sum of the autoregressive coefficients in the reduced-form process of inflation is close to one and, most importantly, is significantly different from the value of zero that would emerge in the unique rational expectations equilibrium (ie determinacy). In contrast, when the analysis is restricted to determinacy the estimates on the artificial data match the ‘true’ coefficients of the model which have been used to generate such artificial data.

Following the literature, determinacy is defined as the unique rational expectation equilibrium. This equilibrium is characterised by the private sector's expectations that whenever actual inflation differs from target the monetary authorities will take the appropriate actions to bring it back immediately. Indeterminacy, in contrast, can be associated with several possible outcomes for inflation and output gap. It is worth emphasising, however, that indeterminacy does *not* imply an explosive path for inflation; rather it implies that the private sectors hold the expectations that the gap between actual inflation and its target value will persist for some time in the future.

The results presented here suggest some caution is needed when interpreting the estimates of the structural NKPC obtained using a pool of observations that mixes different monetary policy regimes. The reason is that inference can be distorted in an important dimension if the econometrician does not recognise that at some points in time monetary policy may be reacting weakly to movements in inflation. In particular, it is possible to introduce additional elements of persistence that are not present in the data generating process of inflation and thus are not an intrinsic, structural feature of the economy. This result can thus provide a rationale for the empirical regularity that inflation persistence coincides with specific monetary policy regimes.

1 Introduction

The New Keynesian Phillips Curve (NKPC) has recently become the building block of many monetary policy models. This relation plays a central role in understanding aggregate fluctuations and quantifying the transmission mechanism of monetary policy. Most of the attraction of the NKPC hinges on the fact that it is derived from first principles, thereby implying that its estimates survive the Lucas (1976) critique.

As shown many times in the literature (see for instance Woodford (2003)), a log-linearised version of the New Keynesian model gives rise to self-fulfilling expectations if the monetary authority does not raise the nominal interest rate sufficiently in response to a deviation of inflation from the target. This implies that sunspot fluctuations can influence the properties of the inflation process even if the 'true' NKPC is a structurally invariant relation.

Using Monte Carlo simulations from a sticky price model, this paper shows that the estimates of a hybrid NKPC are severely biased downward when two conditions are met. First, the data are generated under indeterminacy.[(1)] Second, as is the case for the estimates currently available in the literature, the empirical analysis neglects the possibility of multiple equilibria and hence implicitly limits the solution of the model to the determinacy region. Specifically, in the case of indeterminacy the null hypothesis of no backward-looking component is strongly rejected in spite of the fact that the data-generating process does not exhibit any exogenous or endogenous persistence. The slope of the Phillips Curve takes a value that is not statistically different from zero. Moreover, the sum of autoregressive coefficients in the reduced-form process of inflation is close to one and, most importantly, is significantly different from the value of zero that would emerge in the unique rational expectations equilibrium. In contrast, under determinacy the estimates on the simulated data match the 'true' coefficients used to parameterise the model. For this reason, we refer to the difference between the 'true' and the estimated parameters as 'neglected indeterminacy bias'.

This paper cuts across two bodies of research. The first body is the literature on interest rate rules, inspired by the works of Taylor (1993) and Clarida, Galí and Gertler (2000), which documents a shift in the conduct of monetary policy around the beginning of the 1980s for several industrialised economies. The second strand of work includes Galí and Gertler (1999), Sbordone (2002), Eichenbaum and Fisher (2004), Lindé (2005) and Rudd and Whelan (2005) among many others, and reports conflicting estimates of the NKPC using a number of econometric techniques

(1) Following the literature, determinacy is defined as the unique rational expectation equilibrium. This equilibrium is characterised by the private sector's expectations that whenever actual inflation differs from target the monetary authorities will take appropriate actions to restore immediately the reference value. Indeterminacy, in contrast, can be associated with several possible outcomes for inflation and output gap. It should be noted however that indeterminacy does *not* imply an explosive path for inflation; rather it implies that the private sectors hold the expectations that the gap between actual inflation and its target value will persist for some time in the future.

over various post-war full samples.

The results presented here suggest some caution is needed when interpreting the estimates of the structural NKPC obtained using a pool of observations that mixes different monetary policy regimes. The reason is that neglected indeterminacy can distort inference in an important dimension. In particular, it is possible to introduce additional elements of persistence that are not present in the data-generating process of inflation and thus are not an intrinsic, structural feature of the economy.

This paper also contributes to the literature on inflation persistence. Several authors including Cogley and Sargent (2005) and Benati (2006) show that inflation inertia has been historically limited in the United States and the United Kingdom. In particular, inflation can be characterised as highly persistent only during the 1970s for the United States and before 1992 for the United Kingdom, and these periods are typically associated, in the empirical literature on monetary policy rules, with a weak monetary authority response to inflation. Our simulations reveal that a *passive* monetary policy, in the form of a *less-than-proportional* response of the nominal interest rate to inflation, does actually produce inflation persistence. This result can thus provide a rationale for the empirical regularity on inflation inertia reported by Cogley and Sargent (2005) and Benati (2006).

The paper is organised as follows. Section 2 presents the model that will serve as the data generating process. Section 3 performs a set of Monte Carlo experiments and presents the estimates of the structural process and the reduced-form process of inflation based on the simulated data. The following section reports subsample evidence on the United Kingdom and United States and shows that the data are consistent with the 'neglected indeterminacy bias' hypothesis. Conclusions are discussed in the final part while the appendix describes a method to obtain a solution of the linear rational expectations model under indeterminacy and determinacy.

2 The model

This section describes a log-linearised New Keynesian sticky price model of the business cycle. This model consists of the following three aggregate equations that King (2000) and Woodford (2003) derive from first principles:

$$\begin{aligned}
\pi_t &= \beta E_t \pi_{t+1} + k\left(x_t - z_t\right) && \textbf{(1)}\\
x_t &= E_t x_{t+1} - \tau\left(i_t - E_t \pi_{t+1}\right) + g_t && \textbf{(2)}\\
i_t &= \psi_\pi \pi_t + \psi_x \left(x_t - z_t\right) + u_t && \textbf{(3)}
\end{aligned}$$

where x_t is defined as the deviation of output from a long-run trend, π_t represents inflation, and i_t is the nominal interest rate. Inflation and the interest rate are expressed in percentage deviations from their steady-state values.

Equation **(1)** captures the staggered feature of a Calvo-type world in which each firm adjusts its price with a constant probability in any given period, and independently from the time elapsed from the last adjustment. The discrete nature of price-setting creates an incentive to adjust prices more the higher the future inflation expected at time t. The parameter $0 < \beta < 1$ is the agents' discount factor and k is the slope of the Phillips curve. The shock z_t is identically and independently distributed (iid) with standard deviation σ_z and is meant to capture exogenous shifts in the marginal costs of production.

As there is no capital in the model, the second equation is a standard Euler equation for consumption combined with the relevant market-clearing condition. It brings the notion of consumption smoothing into an aggregate demand formulation by making x_t a positive function of its future value and a negative function of the *ex-ante* real interest rate, $i_t - E_t\pi_{t+1}$. The parameter $\tau > 0$ can be interpreted as intertemporal elasticity of substitution. Preference shifts and government spending shocks are embodied in the iid process g_t which has standard deviation σ_g.

Equation **(3)** characterises the behaviour of the monetary authorities. As in Lubik and Schorfheide (2004), this is an interest rate rule according to which the monetary authorities set the policy rate in response to deviations of inflation and output from their respective targets.[(2)] The target for inflation is normalised to zero. The shock u_t represents an iid monetary policy disturbance with standard deviation σ_u. There is no correlation between innovations.[(3)]

The specification **(1)** to **(3)** with iid shocks and no interest rate smoothing has been deliberately designed to maximise the power of the tests on the (in)significance of the backward-looking components of the Phillips curve. As the process generating the simulated data exhibits no persistence, a rejection of the null hypothesis $(1 - \beta) = 0$ on the simulated data can only be interpreted as a spurious result from neglecting indeterminacy in the estimation procedure.

The linear rational expectations model described by equations **(1)** to **(3)** can be represented in the following canonical form:

$$\Gamma_0(\theta)\, s_t = \Gamma_1(\theta)\, s_{t-1} + \Psi(\theta)\, \varepsilon_t + \Pi(\theta)\, \eta_t \qquad \textbf{(4)}$$

(2) The results below are not affected by excluding z_t from the policy rule.

(3) It should be emphasised that a Taylor rule is used here because it appears a simple way to describe monetary policy empirically, though actual policymaking is far more complex than a simple rule could capture.

where

$$
\begin{aligned}
\theta &= \left[\psi_\pi, \psi_x, \beta, k, \tau\right] \\
s_t &= \left[x_t, \pi_t, i_t, E_t\left(x_{t+1}\right), E_t\left(\pi_{t+1}\right)\right]' \\
\varepsilon_t &= \left[u_t, g_t, z_t\right]' \\
\eta_t &= \left[x_t - E_{t-1}\left(x_t\right), \pi_t - E_{t-1}\left(\pi_t\right)\right]'
\end{aligned}
$$

The matrices Γ_0, Γ_1, Ψ and Π are given by the following expressions:

$$
\Gamma_0 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\tau & 1 & \tau \\ 0 & 0 & 0 & 0 & \beta \end{bmatrix}, \Gamma_1 = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \psi_2 & \psi_1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -k & 1 \end{bmatrix}, \Psi \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & -\psi_2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \Pi = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \psi_2 & \psi_1 \\ 1 & 0 \\ -k & 1 \end{bmatrix}
$$

and they are conformable to the vectors of state variables s_t and s_{t-1}, to the vector of structural disturbances ε_t and to the vector of endogenous forecast errors η_t.

This log-linearised system gives rise to self-fulfilling expectations if the monetary authorities do not raise the nominal interest rate enough in response to a deviation of inflation from the target. For the model used in this paper, Woodford (2003) shows that the following condition must hold for the existence of a unique stable solution:

$$
\psi_\pi \geq 1 - \frac{(1-\beta)\,\psi_x}{k} \tag{5}
$$

In all other cases, a sunspot shock ζ_t will affect the dynamics of output and inflation through the endogenous forecast errors, thereby causing the existence of multiple stable solutions.

3 A Monte Carlo experiment

The main experiment of the paper is now ready to be run. We apply the solution method outlined in the appendix to the New Keynesian model **(1)** to **(3)** and we generate artificial data under both determinacy and indeterminacy. To compute a solution under indeterminacy we follow Lubik and Schorfheide (2004) and present results for two different identifying assumptions. Under the first assumption, the sunspot shocks are orthogonal to the structural shocks and the solution is referred to as 'orthogonality'. Under the second scenario, we assume that the impulse responses $\frac{\partial s_t}{\partial \varepsilon_t'}$ associated with the system **(4)** are continuous at the boundary between the determinacy and the indeterminacy region, and the solution is labelled 'continuity'.

It is worth emphasising that in the data-generating process, inflation and output are purely forward looking, errors are iid and there is no interest rate smoothing. In other words, the model deliberately lacks any source of either endogenous or exogenous persistence.[(4)] We then use the simulated data to estimate the following hybrid version of the Phillips curve relationship:

$$\pi_t = \omega\pi_{t+1} + (1-\omega)\,\pi_{t-1} + kx_t + e_t \qquad \textbf{(6)}$$

where $e_t \equiv -kz_t - \omega(\pi_{t+1} - E_t\pi_{t+1})$ and $\beta = 0.99$. Using the alternative parameterisation $\pi_t = \beta\,[\omega E_t\pi_{t+1} + (1-\omega)\,\pi_{t-1}] + kx_t + v_t$ does not affect the results.

Table A shows the value of the parameters in the data-generating process under indeterminacy and determinacy. These values are borrowed from Lubik and Schorfheide (2004) who use Bayesian techniques to estimate a version of the model **(1)** to **(3)** augmented with autoregressive error terms and interest rate smoothing on US data. To make the indeterminacy bias transparent, we eliminate the persistence in the shocks and in the nominal interest rate by setting the autoregressive coefficients of the processes for g_t, z_t and i_t to zero across all simulations.

The second columns correspond to the pre-Volcker period estimates. The interest rate response to inflation is assumed to be below unity and therefore violates the Taylor principle **(5)**. We use these estimates to generate artificial series of inflation, output and interest rate under the orthogonality and the continuity identifications. The third column reports the values that parameterise the model under determinacy. For the sake of comparison, these coefficients are set to the same values used under indeterminacy, but with two important exceptions: both coefficients of the monetary policy rule do now generate a unique rational expectations solution and they correspond to the estimates in Lubik and Schorfheide (2004) over the post-Volcker sample.

We consider three sample lengths. The baseline case consists of 200 observations, which at quarterly frequencies correspond to 50 years. To explore the extent to which the estimates are sensitive to the sample length we also present results for periods of 80 and 400 observations. The former roughly matches the number of data points available to an econometrician from the beginning of the 1960s to the end of the 1970s.

3.1 Results

Charts 1 and 2 present the results based on 10,000 repetitions. The hybrid New Keynesian Phillips Curve **(6)** is estimated with the generalised method of moments (GMM) and two stage least squares (TSLS) under the hypothesis of rational expectations. Starting from period $t-1$ the instrument set includes past values of inflation, output and nominal interest rate. The selection of the number of lags is based on the Schwartz lag length criterion from an unrestricted vector

(4) For identification purpose, the forward-looking parameter in the Phillips curve is set to 0.99 and the backward-looking parameter to 0.01. We refer to this parameterisation as purely forward looking.

autoregression (VAR) in the three simulated series.

Chart 1 shows the probability distributions of the estimates of the forward-looking component of the Phillips curve. The first two rows reveal that using the data generated under indeterminacy the estimates of ω from a conventional hybrid specification are significantly biased, with the median of the distribution around 0.64 (0.77) under orthogonality (continuity) using GMM. The bias is slightly less pronounced using TSLS. Hence, by neglecting indeterminacy the null hypothesis of no backward-looking component in the Phillips curve is strongly rejected even if the data-generating process is purely forward looking.

The intuition for this result comes from the self-fulfilling nature of inflation expectations under indeterminacy. The private sector anticipates that in response to a positive shock to inflation the monetary authorities will not raise the nominal interest rate sufficiently, and therefore anticipates a negative real rate. The fall in the *ex-ante* real interest rate fuels a boom in real activity, and the boom in turn fuels further inflation. This implies not only that the expectations of high inflation are indeed confirmed but also that inflation remains persistently above target.

An aggressive monetary policy stance to deviations of inflation from target implies, in contrast, that the real interest rate is implicitly set such as to outweigh a rise in expected inflation. This means that a pickup in actual inflation is promptly followed by a reversal towards the target and, in the case of a perfectly credible inflation-targeting regime and a purely forward-looking model, inflation is white noise.

The technical reason for the bias is that the solution of a linear rational expectations model requires that all unstable roots in the matrix of autoregressive coefficients Γ_1^* be suppressed. The New Keynesian model is characterised by two roots, λ_j with $j = 1, 2$. When monetary policy conforms to the Taylor Principle the two roots are unstable, ie the system is determinate, and the solution generates no 'extra' persistence relative to the specification of the model. This means that if the data-generating process is purely forward-looking, as it is here, the backward-looking term of the Phillips curve $(1 - \omega)$ should be zero statistically.

In contrast, indeterminacy is characterised by only one *unstable* root, thereby implying that the solution now generates 'extra' persistence through the *stable* root λ_1 – see equation **(A-6)** in the appendix. This is confirmed by the third row of Chart 1. Under determinacy, the median estimates of ω are not statistically different from the true value of 0.99 at the 1% significance level, though they are somewhat smaller numerically. As shown below using simulations from a longer sample, this is likely to reflect a small sample problem.

Chart 2 shows the results for the slope of the Phillips curve. The data are generated under the assumption that the true parameter is 0.77 but only the estimates on the series simulated under determinacy are consistent with this value. In contrast under indeterminacy, whether using the orthogonality or the continuity assumption, the estimates of k are severely biased towards zero and largely below the 'true' value.

Indeterminacy may also have important implications for the reduced-form properties of the (simulated) data. To explore this possibility we estimate with OLS the following process for inflation

$$\pi_t = \mu + \phi_1 \pi_{t-1} + \phi_2 \pi_{t-2} + \ldots + \phi_p \pi_{t-p} + \xi_t \tag{7}$$

with $3 < p < 8$. Chart 3 reports the probability distributions of the sum of the autoregressive coefficients in equation **(7)**. Indeterminacy generates sizable persistence, though the reduced-form persistence of a purely forward-looking model solved for the unique rational expectations equilibrium is zero. In contrast, the estimates on the inflation series are centred in zero under determinacy.

This finding also suggests that weak instruments are unlikely to be a concern under indeterminacy where inflation is quite a persistent process. Furthermore, while in principle it seems more reasonable to question the relevance of the instruments under determinacy, the third rows of Chart 1 and Chart 2 show that in practice the GMM estimates match the 'true' values of parameters under determinacy.

The results so far reveal the extent to which the estimates of the New Keynesian Phillips Curve are sensitive to a different monetary policy response to inflation. Chart 4 presents the estimates and the confidence intervals of the parameters of the inflation process as a function of ψ_π. The estimates are computed for a grid of 20 points over the interval [0, 2]. The interesting result from this experiment is that - with the exception of the slope of the Phillips curve - the size of the bias is a negative function of the distance of ψ_π from the border between the indeterminacy and the determinacy region. As far as the forward-looking component of the Phillips curve is concerned, only a monetary authority response to inflation close to zero would deliver an unbiased estimate of ω within the indeterminacy region.

3.2 Robustness analysis

To investigate the relevance of the sample length for our findings, Chart 5 presents results for 80 and 400 observations using the orthogonality solution. As the previous results were robust to running 1, 000 simulations, we set the number of repetitions to the latter value in an effort to make the computational burden lighter.

The bias is still sizable in both experiments, though the estimates over a longer period are, unsurprisingly, more accurate and precise. Moreover, the median estimates of the forward-looking component of the Phillips curve in the large sample is now close to 0.99. This suggests both that the 'neglected indeterminacy bias' is more than simply a small sample bias, and also that it is not likely to be merely a peculiarity of instrumental variable estimators.

The results are also robust to using a 'mixed' sample of 160 observations in which the monetary policy rule switches from passive to active midway through the period. Specifically, the first 80 observations are generated under indeterminacy while the second half of the observations are generated under determinacy. The estimate of the forward-looking component of the NKPC is 0.81 (0.84) using the orthogonality (continuity) identification, the slope takes a value of 0.06 (0.12) while the sum of the autoregressive coefficients of the reduced-form process is 0.56 (0.72).

Chart 6 presents an experiment where, conditional on the parameters for the orthogonality and continuity cases, the data are generated using different values of the standard deviation of the sunspot shocks, σ_ζ. The estimates are computed for a grid of 15 points in the interval [0, 1.4]. The first row shows that the bias of the estimates of the forward-looking component increases with σ_ζ for empirically plausible values of this standard deviation. For values larger than 0.3, which exceeds the estimates in Lubik and Schorfheide (2004), the bias of the forward-looking term appears stable.

The estimates of the slope of the Phillips curve seem virtually unchanged by the size of the standard deviation. As indeterminacy can influence aggregate fluctuations both by affecting directly the equilibrium dynamics through the sunspot shock and by affecting indirectly the transmission of the structural shocks to the endogenous variables, this result suggests that the bias in the slope is mostly due to the indirect effect. The last row shows that the sum of the autoregressive coefficients of the reduced-form process of inflation is a decreasing function of σ_ζ. This is probably due to the fact that a larger variance of the sunspots shocks translates into a larger variance of the endogenous state variables without implying a higher covariance between inflation and its own lags. The overall effect is therefore a reduction in the OLS estimates.

4 Empirical evidence

The previous section showed that pooling observations from different monetary policy regimes can be highly misleading for the inference based on the full-sample estimates of the NKPC. In this section, we present some evidence on UK and US quarterly data that appears consistent with the 'neglected indeterminacy bias' hypothesis.

As a preview of the results, the policy regimes that the empirical literature on monetary policy rules typically associates with a weak interest rate response to inflation are characterised by a higher degree of inertia in the structural process of inflation.

For the purpose of estimation, the NKPC is specified in the following hybrid version:

$$\pi_t = \omega_f \pi_{t+1} + \omega_b \pi_{t-1} + kx_t + \upsilon_t \qquad \textbf{(8)}$$

where $\upsilon_t \equiv -\omega_f(\pi_{t+1} - E_t\pi_{t+1})$. Inflation is measured as the annualised quarterly change in the GDP deflator. As far as excess demand is concerned, we present results using two alternative measures of the business cycle. The first measure is the output gap. For the United States, this corresponds to the deviation of real GDP from the official estimates of real potential output provided by the Congressional Budget Office (CBO), whereas for the United Kingdom it is the residuals from a regression of real GDP on a quadratic trend. The second measure is the labour share calculated as the ratio of nominal compensation to employees to nominal GDP. The data have been obtained in January 2005 from the Bank of England and the Federal Reserve Bank of St. Louis.

For the United Kingdom, we consider the period 1979 Q2 to 2003 Q4. The starting point corresponds to the change of government and associated move towards a more active use of interest rates to control inflation. Moreover, the data on the UK labour market, including unit labour costs, began to be systematically collected and published only in 1979 with the establishment of the Labour Force Survey. The full sample is divided around the fourth quarter of 1992 when the Government announced for the first time an explicit target for inflation. Given the short length of the later period, we compare the estimates of the pre-1992 regime with the full-sample estimates. Nelson (2003) shows that the pre and post-1992 periods are characterised by a marked difference in the monetary policy stance in that the nominal interest rate has been raised more than proportionally in response to inflation movements only after 1992.

For the United States, we consider the period 1966 Q1 to 1997 Q4. The beginning of the sample corresponds to the date the Federal funds rate first traded consistently above the discount rate. The first subsample ends in 1979 Q2 when Paul Volcker was appointed Chairman of the Fed and changed the implementation of monetary policy to counter inflation more actively. The later subsample begins in 1982 Q3 and therefore excludes the period in which Bernanke and Mihov (1998) document that the operating procedure of the Fed temporarily switched from Federal funds rate to non-borrowed reserves targeting. The end of sample is chosen so as to make our results comparable to the available literature which typically uses observations until 1997 Q4 (see Galí and Gertler (1999) and Lubik and Schorfheide (2004)). The results are not affected, however, by expanding the sample until 2003 Q4. Clarida, Galí and Gertler (2000) pioneered a vast empirical literature finding that the monetary policy stance of the Fed can be described as *passive* during the pre-Volcker regime and *active* during the post-Volcker regime.

4.1 The estimates

Under rational expectations, the forecast error υ_t is orthogonal to the current information set and equation **(8)** can be estimated with GMM using an optimal weighting matrix that accounts for possible heteroskedasticity and serial correlation in the error terms. In practice, we employ a three-lag Newey-West estimate of the covariance matrix where the number of lags is selected according to standard lag length criteria on a four-variate VAR in inflation, output gap, unit labour cost and nominal interest rate. Starting from date $t - 1$, three lags of these four variables are included as instruments corresponding to $nine$ overidentifying restrictions that can be tested for. The null hypothesis of valid overidentifying restrictions is never rejected.

Table B reports the results for the United Kingdom. Regardless of the measure of excess demand, the pre-1992 estimates of the forward-looking component of the Phillips curve are statistically smaller than their full-sample counterparts, consistent with the prediction of 'neglected indeterminacy bias'. In particular, the hypothesis of no backward looking in the NKPC can only be rejected in the earlier period. The estimates of the slope display a positive sign only when the labour share measure is used and they are larger in the full sample, though they are not statistically different from zero.

Restricting $\omega_b = (1 - \omega_f)$ does not alter our conclusions. Furthermore, letting the later sub sample begin in the first quarter of 1993 produces results, not reported but available upon request, which are very similar to the full-sample estimates. Given the limited number of observations available since the introduction of the inflation-targeting regime, however, we prefer not to give much weight to the finding from the later sub sample. Interestingly, these results are consistent with and complement the reduced-form evidence in Kuttner and Posen (1999), Batini and Nelson (2001) and Benati (2006) who show that the persistence of inflation in the United Kingdom has dramatically declined since the announcement of an explicit target for inflation, moving from a value between 0.79 and 0.96 before 1992 to a value not statistically different from zero afterwards.

The findings for the United States are displayed in Table C and appear to bear out the evidence for the United Kingdom. The estimates of the forward-looking component are larger over the most recent monetary policy regime and they are significantly so using the labour share measure. Unlike the United Kingdom, the later sample seems characterised by a significant, albeit smaller, backward-looking term. The slope of the Phillips curve takes a positive sign only using unit labour costs and, consistently with the simulations in the previous section, it is statistically different from zero only in the post-Volcker period. The full-sample estimates based on the labour share measure, not reported but available upon request, read a slope coefficient of 0.02 which is not statistically different from zero. The reduced-form analysis in Cogley and Sargent (2005 and 2002) reveals that the persistence of US inflation increased during the second half of the 1960s and during the 1970s and then fell in the 1980s and 1990s. Our results are compatible with the notion of a fall in inflation inertia.

Obviously, the results in this section are only suggestive and it is beyond the scope of this paper to discriminate whether the historical decline in inflation inertia documented by Cogley and Sargent

(2005 and 2002) and Benati (2006) represents a genuine structural break of an intrinsic feature of the economy, the effect of indeterminacy over the earlier samples, or some other consequence of monetary policy. Nevertheless, it is intriguing to observe that the structural and the reduced-form inertia of the inflation process appear a peculiarity of the periods associated with a passive monetary policy reaction function. Following a similar line of argument, Cogley and Sbordone (2005) show that a constant-parameter version of the NKPC can be consistent with a drifting-parameter VAR, thereby suggesting that a structural break in the Phillips curve does not seem to account for the changing persistence of US inflation.

4.2 Weak instruments

Weak instruments are an important issue which we must confront to validate our estimates. Stock and Yogo (2003) tabulate critical values for the multiple endogenous regressor analogue of the first-stage F-statistics and define weak instruments in terms of bias and in terms of size of the test. In particular, a set of instruments can be deemed strong if the analogue of the F-statistics is sufficiently large that either the instrumental variable bias is no more than x% of the inconsistency of OLS or a 5% hypothesis test rejects no more than y% of the time. The first definition is useful for the purpose of inference whereas the second seems appropriate for hypothesis testing. Unfortunately, there is no particular guidance for the selection of x and y other than the researcher's tolerance.

In general, we find that our set of instruments can be deemed strong using $x = 10$ and $y = 15$ — even more ambitious tolerance levels can be met in several cases — with two exceptions. Both of them correspond to the pre-1992 regime in the United Kingdom. We then expand the list of instrumental variables in these two cases to include in addition wage inflation, reasoning that important reforms in the UK labour market took place during the 1980s, and it seems plausible to think they had an impact on inflation. Moreover, we reduce the number of lags of the instrumental variables from three to two in an effort to minimise the potential small-sample bias that may arise when too many overidentifying restrictions are imposed. The second and the third columns of Table B show that the expanded set of instruments can also be deemed strong over the pre-1992 period and the estimates reported in these columns refer to the expanded instrument set.

5 Conclusions

This paper begins to bridge the gap between two bodies of research on inflation dynamics. The first body uses a microfounded NKPC to estimate the structural relationship between inflation and marginal costs. On the promise of identifying truly structural parameters, this literature mainly focuses on the full post-war period with a typical sample starting in 1960. The second body uses the New Keynesian model to demonstrate that a weak interest rate reaction to inflation generates sunspot fluctuations which can sizably influence the macroeconomic dynamics.

Using a purely forward-looking New Keynesian model as the data-generating process, this paper computes the solutions of the rational expectations model for two classes of the interest rate rule. These parameterisations roughly correspond to the shift in the conduct of monetary policy that occurred in a number of industrialised countries around the beginning of the 1980s. Specifically, one class of coefficients represents a passive monetary policy stance according to which the monetary authority can generate indeterminacy by moving the nominal interest rate insufficiently in response to inflation pressures. The second class of parameterisations describes activist conduct that conforms to the Taylor principle and therefore produces a unique stable solution.

Monte Carlo simulations demonstrate that the estimates of the forward-looking component and the slope of the NKPC can be severely biased downward whenever two conditions hold. First, the data are generated under a passive monetary policy rule. Second, the estimation procedure arbitrarily rules out the possibility of indeterminacy. Furthermore, this paper shows that the bias becomes larger the closer the interest rate response to inflation approaches the boundary between indeterminacy and determinacy. These results are robust to the number of observations in the simulated sample and to the selection of the instrumental variable estimator. Finally, when the above two conditions are met the sum of autoregressive coefficients in the reduced-form representation of the inflation process is close to one, even though the data-generating process exhibits no intrinsic persistence.

Empirical evidence on the NKPC using data for the UK and US economies shows that inflation inertia is far more pronounced during the monetary policy regimes characterised by a less-than-proportional response of nominal interest rate to inflation. This result holds independently from whether the measure of excess demand is labour share or output gap, and is in line with the prediction of the 'neglected indeterminacy bias' hypothesis. Moreover, our structural estimates are consistent with and complement the reduced-form evidence in Benati (2006) for the United Kingdom and in Cogley and Sargent (2005) for the United States that the change in inflation persistence is concomitant with a policy regime shift.

Shifts in the monetary policy rule therefore have serious implications for inference based on the NKPC. This finding indicates some caution is needed when interpreting the results from full-sample analyses which pool observations from different monetary policy regimes. Importantly, the neglected indeterminacy bias can arise even if the Phillips curve is a structurally invariant relation.

An interesting avenue for future research would be to estimate a time-varying structural model that at each point in time allows the possibility of a switch between the indeterminacy and the determinacy solution. Furthermore, a richer model of the business cycle may relax the tight link between the degree of activism in the policy rule and indeterminacy, with consequences for the 'neglected indeterminacy bias' that are worth exploring.

Appendix A: Solution of the LRE model

In order to transform the canonical form and solve the model, we follow Sims (2001) and exploit the QZ decomposition of the matrices Γ_0 and Γ_1. This corresponds to computing the matrices Q, Z, Λ and Ξ such that $QQ' = ZZ' = I_n$, Λ and Ξ are upper triangular, $\Gamma_0 = Q'\Lambda Z$ and $\Gamma_1 = Q'\Xi Z$. Moler and Stewart (1973) prove that the QZ decomposition always exists. Defining $w_t = Z's_t$ and pre-multiplying **(4)** by Q, we obtain:

$$\begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ 0 & \Lambda_{22} \end{bmatrix} \begin{bmatrix} w_{1,t} \\ w_{2,t} \end{bmatrix} = \begin{bmatrix} \Xi_{11} & \Xi_{12} \\ 0 & \Xi_{22} \end{bmatrix} \begin{bmatrix} w_{1,t-1} \\ w_{2,t-1} \end{bmatrix} + \begin{bmatrix} Q_{1.} \\ Q_{2.} \end{bmatrix} \left(\Psi \varepsilon_t + \Pi \eta_t \right) \qquad \textbf{(A-1)}$$

where the vector of generalised eigenvalues λ, which is the ratio between the diagonal elements of Ξ and Λ, has been partitioned such that the lower block collects all the explosive eigenvalues. The matrices Ξ, Λ and Q have been partitioned accordingly, and therefore $Q_{j.}$ collects the blocks of rows that correspond to the stable ($j = 1$) and unstable ($j = 2$) eigenvalues respectively.

The explosive block of **(A-1)** can be rewritten as:

$$w_{2,t} = \Lambda_{22}^{-1} \Xi_{22} w_{2,t-1} + \Lambda_{22}^{-1} Q_{2.} \left(\Psi \varepsilon_t + \Pi \eta_t \right)$$

A non-explosive solution of the linear rational expectations model **(4)** for s_t requires $w_{2,t} = 0$ $\forall t \geq 0$. This can be obtained by setting $w_{2,0} = 0$ and choosing for every vector ε_t the endogenous forecast error η_t that satisfies the following condition:

$$\Psi^* \varepsilon_t + \Pi^* \eta_t = 0 \qquad \textbf{(A-2)}$$

where $\Psi^* = Q_{2.}\Psi$ and $\Pi^* = Q_{2.}\Pi$.

In general, we can be confronted with three cases. If the number of endogenous forecast errors is equal to the number of unstable eigenvalues, the system is determined and the stability condition **(A-2)** uniquely determines η_t. If the number of endogenous forecast errors does exceed the number of unstable eigenvalues, the system is undetermined and sunspot fluctuations can arise. If the number of endogenous forecast errors is smaller than the number of unstable eigenvalues, the system has no solutions. This condition generalised Blanchard and Kahn's (1980) procedure of counting the number of unstable roots and predetermined variables.[5]

A general solution for the endogenous forecast error can be computed through a singular value decomposition of $\Pi^* = UDV'$. Lubik and Schorfheide (2003) show that this solution takes the

(5) Sims' solution method has the advantage that it does not require the separation of predetermined variables from 'jump' variables. Rather, it recognises that in equilibrium models expectational residuals are attached to equations and that the structure of the coefficient matrices in the canonical form implicitly selects the linear combination of variables that needs to be predetermined for a solution to exist.

following form:

$$\eta_t = \left(-V_{.1}D_{11}^{-1}U_{.1}'\Psi^* + V_{.2}M_1\right)\varepsilon_t + V_{.2}M_2\zeta_t \tag{A-3}$$

where D_{11} is the upper-left diagonal block of D, U and V are orthonormal matrices, and M_s with $s = 1, 2$ are the matrices that govern the influence of the sunspot shock on the model dynamics.

Solution **(A-3)** can be combined with **(4)** to yield the following law of motion for the state vector:

$$s_t = \Gamma_1^* s_{t-1} + \left[\Psi^* - \Pi^* V_{.1}D_{11}^{-1}U_{.1}'\Psi^*\right]\varepsilon_t + \Pi^* V_{.2}\left(M_1\varepsilon_t + M_2\zeta_t\right) \tag{A-4}$$

where for expositional convenience the notation (θ) is suppressed whenever we refer to a single vector of parameters equation-wide.

Equation **(A-4)** shows that indeterminacy has two consequences. First, sunspot fluctuations ζ_t can influence equilibrium dynamics as long as M_2 is a non-zero matrix. Second, the transmission of fundamental shocks ε_t to the endogenous variables is no longer uniquely identified as the elements of M_1 are not pinned down by the structure of the linear rational expectations model. Under determinacy $V_{.2} = 0$ and therefore the sunspot shock has no effect on aggregate fluctuations.

To compute the solutions of the model under indeterminacy, it is necessary to impose some additional restrictions on the endogenous forecast errors. In practice, we normalise $M_2 = 1$ such that ζ_t can be reinterpreted as a reduced-form sunspot shock. Moreover, we follow Lubik and Schorfheide (2003) and focus on two alternative identification schemes for M_1 which are labelled orthogonality and continuity. The first auxiliary assumption is that the effects of fundamental and sunspot shocks on the forecast error are *orthogonal* to each other. This corresponds to assuming $M_1 = 0$.

The second identifying scheme corresponds to choosing M_1 such that the impulse responses $\partial s_t/\partial\varepsilon_t'$ are *continuous* at the boundary between determinacy and indeterminacy region. Let Θ^I and Θ^D be the sets of all possible vectors of parameters, $\theta's$, in the indeterminacy and determinacy region respectively. For every vector $\theta \in \Theta^I$ we identify a corresponding vector $\widetilde{\theta} \in \Theta^D$ that lies on the boundary of the two regions and choose M_1 such that the response of s_t to ε_t conditional on θ mimics the response conditional on $\widetilde{\theta}$. In practice, we minimise the least squares deviations of the two impulse responses such that:

$$M_1 = \left[B_2'(\theta)B_2(\theta)\right]^{-1} B_2'(\theta)\left[B_1(\widetilde{\theta}) - B_1(\theta)\right] \tag{A-5}$$

where

$$B_1(\widetilde{\theta}) = \frac{\partial s_t}{\partial\varepsilon_t'}(\widetilde{\theta})$$

and

$$B_1(\theta) + B_2(\theta)M_1 = \left[\Psi^*(\theta) - \Pi^*(\theta)V_{.1}(\theta)D_{11}^{-1}(\theta)U_{.1}'(\theta)\Psi^*(\theta)\right] + \Pi^*(\theta)V_{.2}(\theta)M_1 = \frac{\partial s_t}{\partial\varepsilon_t'}(\theta, M_1)$$

The new vector $\widetilde{\theta}$ is obtained from θ by replacing ψ_1 with condition **(5)**, which marks the boundary between the determinacy and indeterminacy region in the system **(1)** to **(3)**.[6]

The solution of **(A-1)** is now fully characterised and for any given vector of parameters of the model it is possible to compute the evolution of the state variables under both determinacy and indeterminacy. In particular, the forecast error η_t and the law of motion for the latent state:

$$w_{1,t} = \Lambda_{11}^{-1}\Xi_{11}w_{1,t-1} + \Lambda_{11}^{-1}Q_{1.}\left(\Psi\varepsilon_t + \Pi\eta_t\right) \qquad \textbf{(A-6)}$$

can be used to obtain $s_t = Zw_t$. The ratio $\Lambda_{11}^{-1}\Xi_{11} = \lambda_1(\theta)$ in **(A-6)** represents the generalised *stable* eigenvalue of $\Gamma_1^*(\theta)$ in the system **(A-4)** and it is the source of 'extra' persistence in the solution of the model **(1)** to **(3)** under indeterminacy.

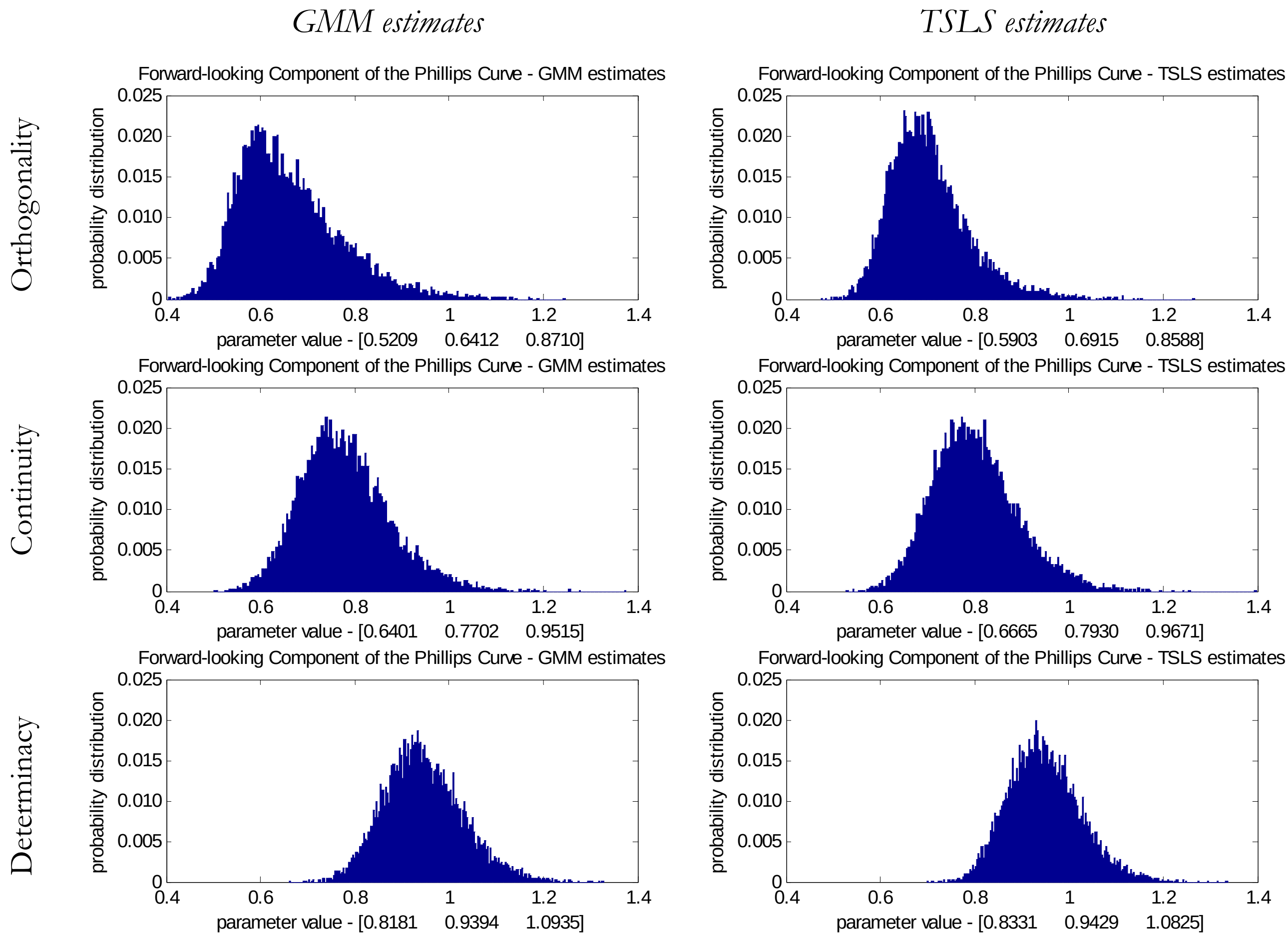
(6) Lubik and Schorfheide (2004) notice that this way of computing the vector M_1 relates to the search for the minimal-state-variable solution advocated by McCallum (1983), ie the most meaningful solution from an economic perspective among the n-possible ones under indeterminacy.

Appendix B: Tables and charts

Table A: Model parameters		
Parameters	Indeterminacy	Determinacy
ψ_π	0.77	2.19
ψ_x	0.17	0.30
ρ_R	0.60	0.84
β	0.99	
κ	0.77	*0.77*
τ^{-1}	1.45	*1.45*
σ_R	0.23	*0.23*
σ_g	0.27	*0.27*
σ_z	1.13	*1.13*
σ_ξ	0.20	-

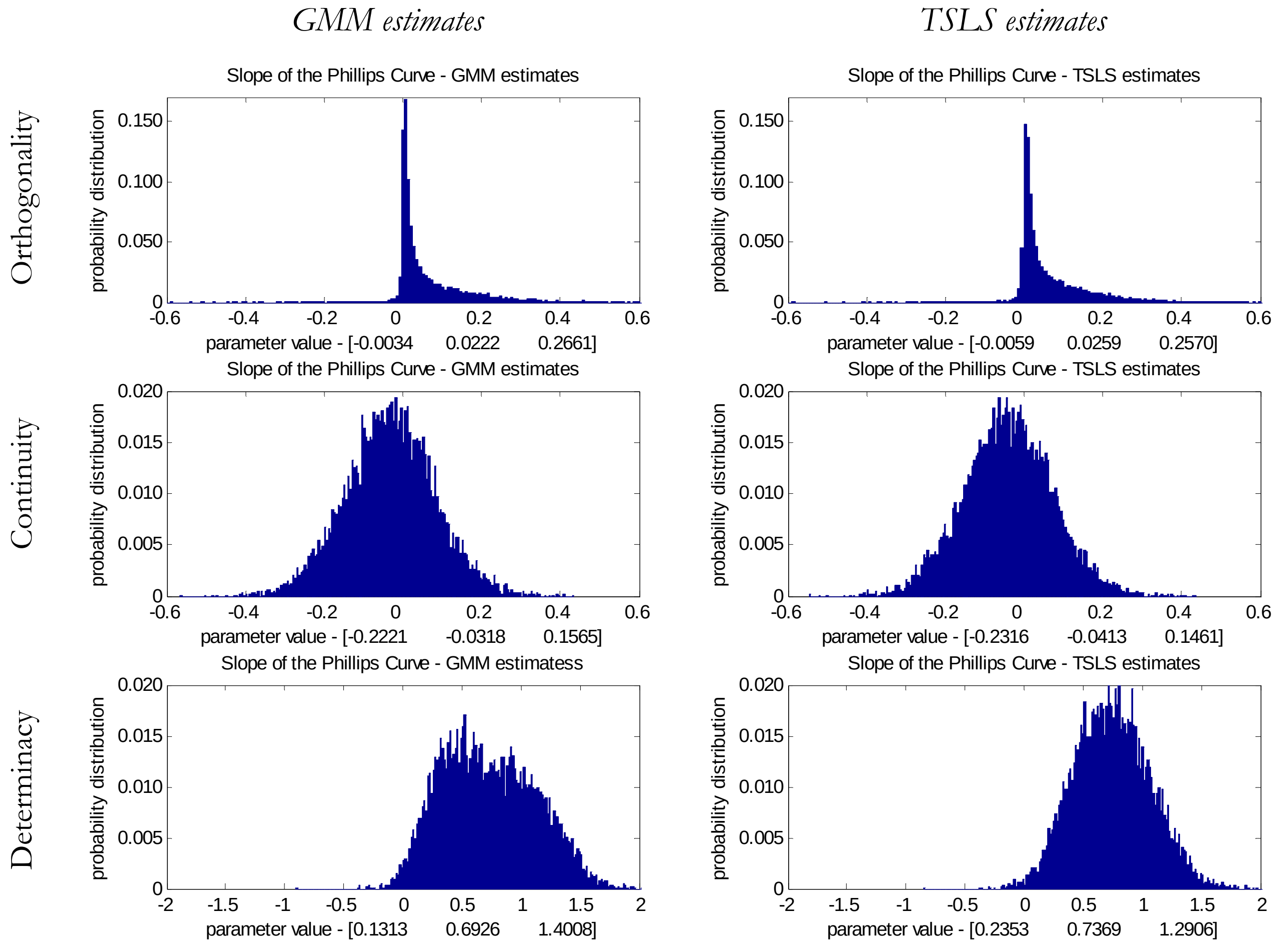
Note: The parameterisation of the data-generating process under indeterminacy corresponds to the estimates in Lubik and Schorfheide (2004) over the pre-Volcker period. The solutions of the model under indeterminacy use the estimates in the second column. The solution of the model under determinacy uses the estimates in the third column.

Chart 1: Forward-looking component in the Phillips curve



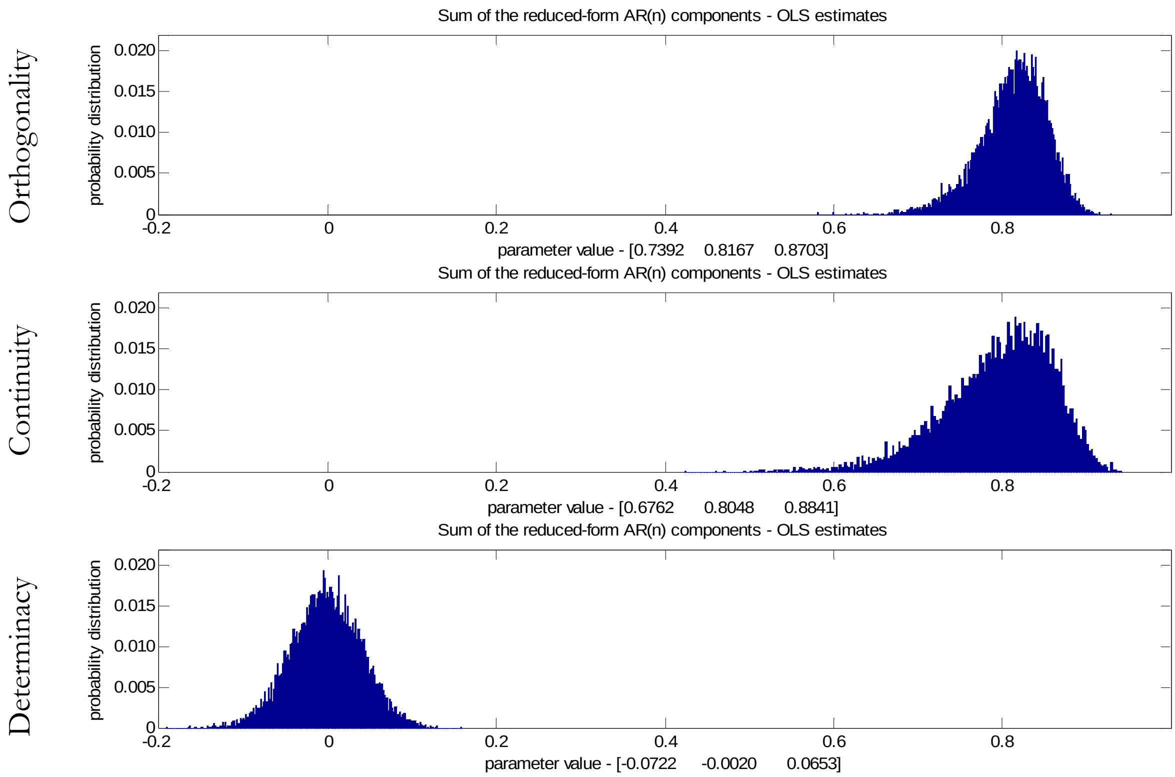
Note: The data-generating process is a purely forward-looking model. The parameters are set to the values in Table A. Estimates are based upon 10,000 repetitions of a sample of 200 observations. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. Numbers in squared brackets represent the 5th, the 50th and the 95th percentile of the confidence interval, respectively.

Chart 2: Slope of the Phillips curve



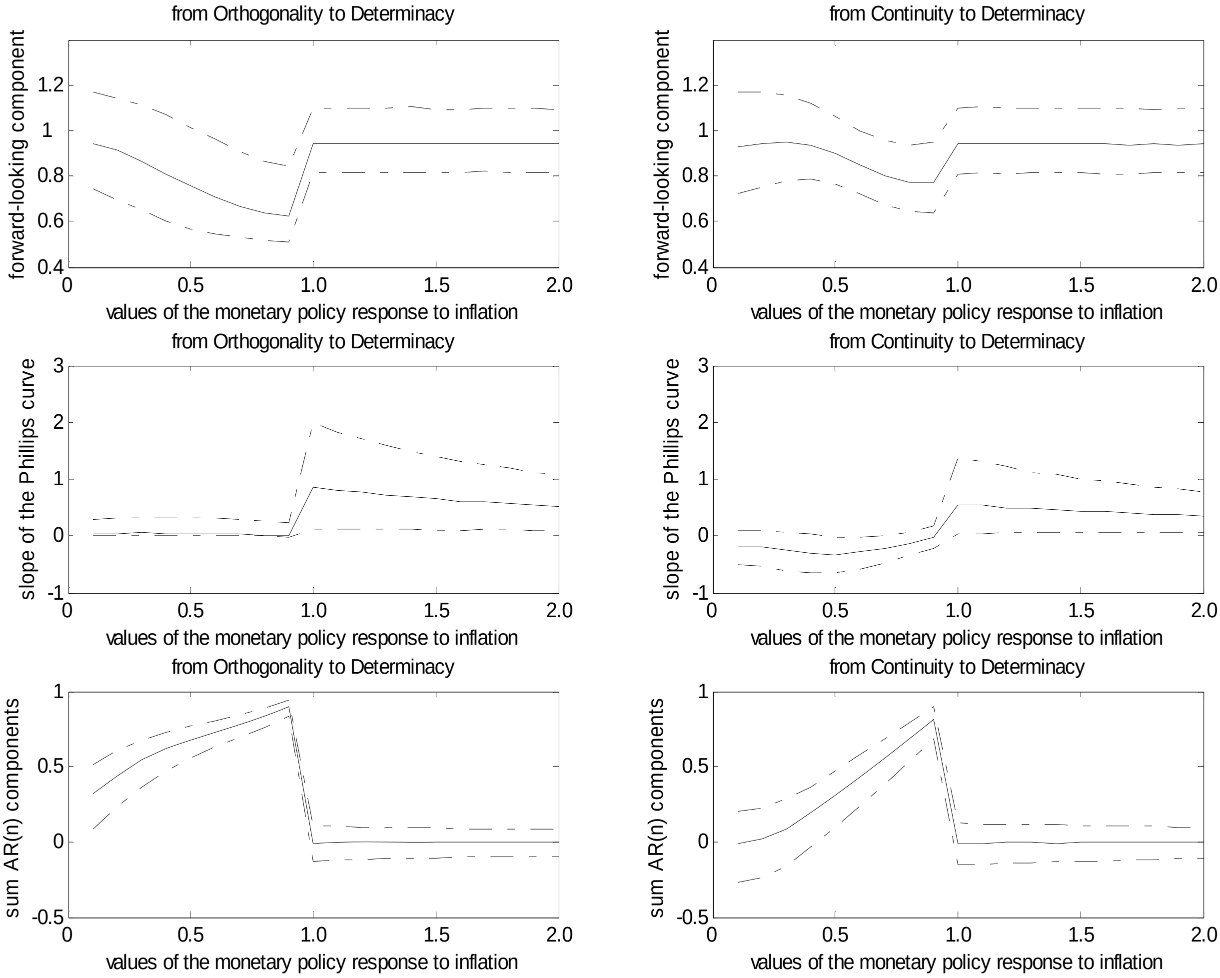
Note: The data-generating process is a purely forward-looking model. The parameters are set to the values in Table A. Estimates are based upon 10,000 repetitions of a sample of 200 observations. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. Numbers in squared brackets represent the 5th, the 50th and the 95th percentile of the confidence interval, respectively.

Chart 3: Sum of the reduced-form AR(n) components – OLS estimates



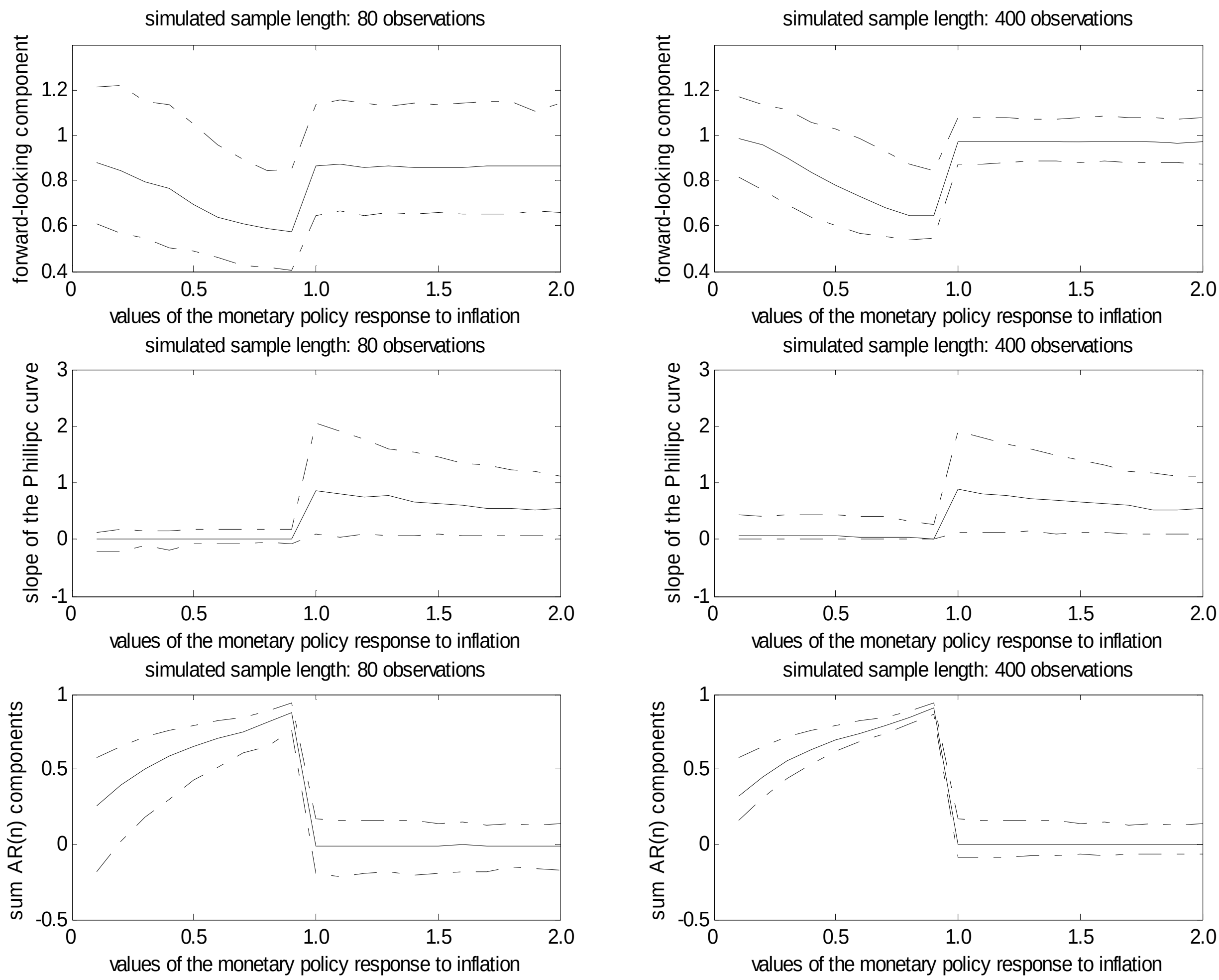
Note: The data-generating process is a purely forward-looking model. The parameters are set to the values in Table A. Estimates are based upon 10,000 repetitions. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. Numbers in squared brackets represent the 5th, the 50th and the 95th percentile of the confidence interval, respectively.

Chart 4: GMM estimates as a function of the monetary policy response to inflation
- from indeterminacy to determinacy –



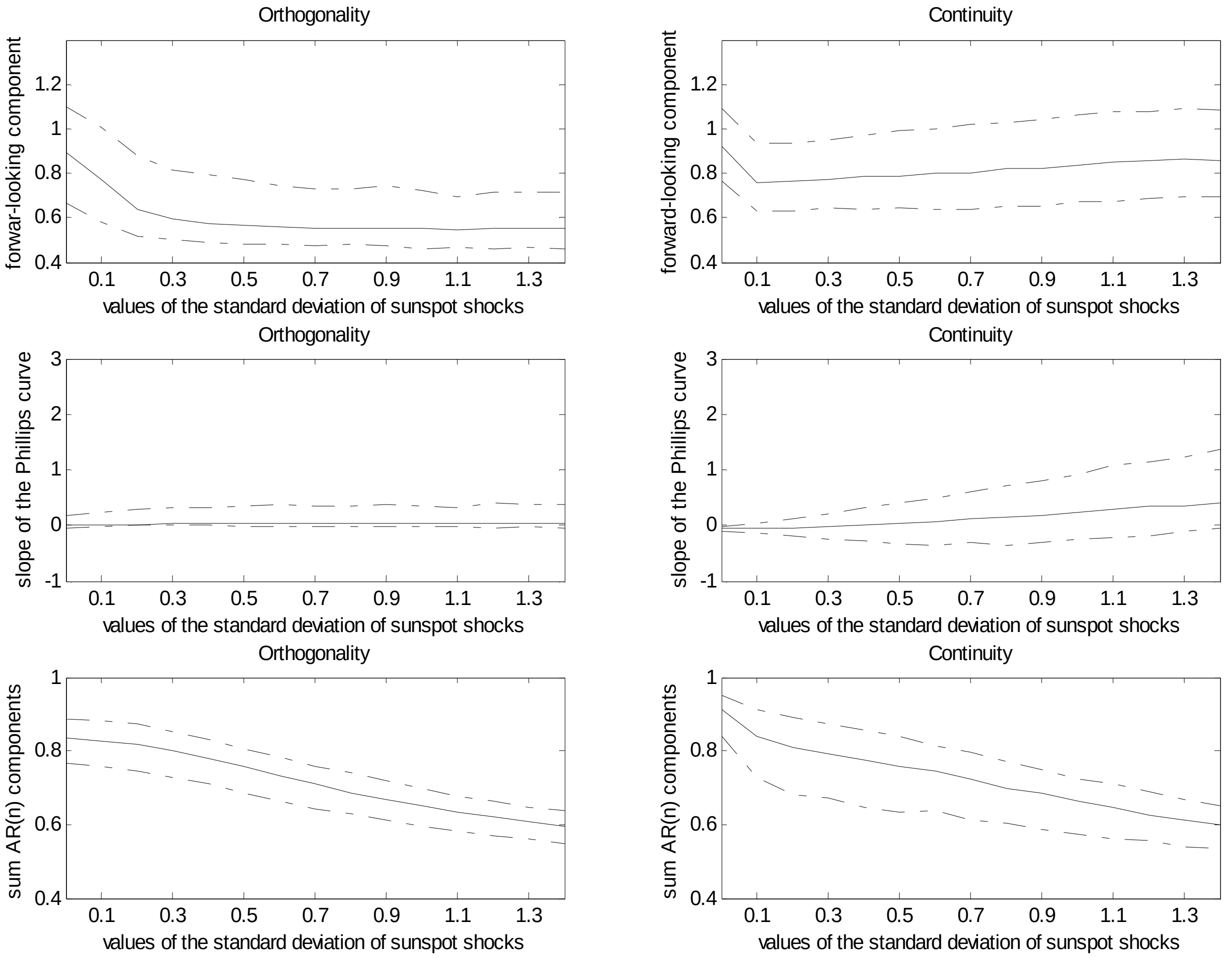
Note: The data-generating process is a purely forward-looking model. The parameters are set to the values in Table A. Estimates are based upon 10,000 repetitions of a sample of 200 observations. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. The dotted line corresponds to the point estimate whereas the dashed lines refer to the 5th and the 95th percentile of the confidence interval, respectively.

Chart 5: GMM estimates as a function of the monetary policy response to inflation
- from indeterminacy to determinacy with a different number of observations –



Note: The data-generating process is a purely forward-looking model. The parameters in the indeterminacy region are set to the values of Case 1 in Table A. Estimates are based upon 1,000 repetitions of two samples of 80 and 400 observations respectively. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. The dotted line corresponds to the point estimate whereas the dashed lines refer to the 5th and the 95th percentile of the confidence interval, respectively.

Chart 6: GMM estimates as a function of the standard deviation of the sunspot shock



Note: The data-generating process is a purely forward-looking model. The parameters are set to the values in Table A. Estimates are based upon 1,000 repetitions of a sample of 200 observations. Each simulated sample is initiated with 100 extra observations to get a stochastic initial state, which are then discarded. The dotted line corresponds to the point estimate whereas the dashed lines refer to the 5[th] and the 95[th] percentile of the confidence interval, respectively.

Table B: GMM estimate of the NKPC – United Kingdom

sample	1979:2 – 1992:4		1979:2 – 2003:4	
specification	*Labour share*	*Output gap*	*Labour share*	*Output gap*
ω_f	0.594*** (0.126)	0.633*** (0.137)	1.002*** (0.134)	1.063*** (0.124)
ω_b	0.396*** (0.119)	0.354*** (0.132)	0.016 (0.128)	-0.073 (0.126)
κ	0.009 (0.072)	-0.023 (0.043)	0.037 (0.046)	-0.079* (0.042)
J-stat p-value	0.333	0.346	0.767	0.929
Analogue F-stat	21.567#	17.858#	23.552#	25.472#

Notes: Standard errors using a three-lag Newey-West estimate of the covariance matrix are reported in brackets. If not specified otherwise, the instrument set includes three lags of inflation, output gap, labour share and nominal interest rate. *J* refers to the statistics of Hansen's test for *m* over-identifying restrictions which is distributed as a $\chi^2(m)$ under the null hypothesis of valid over-identifying restrictions. *Analogue F* refers to the minimum eigenvalue of the matrix analogue of the first-stage F-statistics. The test rejects the null hypothesis of weak instruments in favour of the alternative of strong instruments if *Analogue F* exceeds the critical value. The critical value is computed at the 5% significance level. The superscript ***, ** and * denote the rejection of the null hypothesis that the true coefficient is zero at the 1%, 5% and 10% significance levels, respectively. The superscript # denotes the rejection of the null hypothesis of weak instruments.

Table C: GMM estimate of the NKPC – United States

sample	1966:1 – 1979:2		1982:3 – 1997:4	
specification	*Labour share*	*Output gap*	*Labour share*	*Output gap*
ω_f	0.605*** (0.075)	0.721*** (0.080)	0.815*** (0.093)	0.802*** (0.068)
ω_b	0.376*** (0.075)	0.274*** (0.083)	0.185** (0.084)	0.188*** (0.063)
κ	0.120 (0.096)	-0.072 (0.062)	0.194** (0.089)	-0.034 (0.046)
J-stat p-value	0.606	0.471	0.515	0.325
Analogue F-stat	21.661#	27.218#	33.143#	18.103#

See notes to Table B for details.

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