Cointegration-based Tests of the New Keynesian Model of Inflation

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Abstract

We show that the New-Keynesian (NK) model of inflation can be interpreted as a forward-looking cointegrated model. This allows us to model firms' expectations about marginal costs in a simple VAR framework and develop relatively simple formal tests of the model which bypass the econometric problems faced by other approaches. We show that a series of Granger-causality tests can indicate whether there is *some* forward-looking component to price setting. We implement these tests using quarterly data for the UK and the US. We find that the NK model is formally rejected but that there is strong evidence of a forward looking component to price setting.

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1 Introduction

In this paper we show that the New-Keynesian (NK) model of inflation can be interpreted as a 'forward-looking cointegrated model' in the sense of Campbell and Shiller (1988). We exploit this feature to develop a series of new tests of the NK model and we implement them using quarterly data for the UK from 1963Q2-2000Q4, and for the US from 1960Q1-2000Q4.

The empirical failure of the NK model is now widely recognized[1] and we confirm this failure by the application of the tests we develop in this paper. However, our test procedures have a number of advantages over those commonly adopted in the literature. Firstly, they exploit a feature of forward-looking cointegrated models which, in this context, implies that the error from the implied cointegrating equation involving prices and nominal marginal costs - the error-correction term - incorporates all *private* information available to firms about future movements in their marginal costs. This feature allows us to model firms' expectations about marginal costs in a very simple VAR framework and, through a series of Granger-causality tests, to test whether there is *some* forward-looking component to price setting as the NK model suggests. In the event of the NK model being formally rejected, these tests may give some indication of which parts of the model need to be modified and which do not. Secondly, our tests adopt a 'backward-looking' econometric framework to test what is essentially a forward-looking model of price determination. They thereby avoid certain econometric problems encountered by, for example, Galí and Gertler (1999) and Galí, Gertler, and López-Salido (2001), notably the selection of an appropriate set of instruments for the lead term in inflation. Thirdly, by stressing the cross-equation restrictions that the model places on a VAR involving nominal marginal costs and an error-correction term, our approach allows relatively simple, formal tests of the NK model. Indeed, in one form, these restrictions suggest a test which involves no more than an OLS regression of inflation and an F- or t-test of the significance of variables other than lagged inflation and a lagged error-correction term.[2]

We find strong evidence that, both in the UK and the US, the error-correction variable does Granger-cause marginal costs, which suggests that in both countries there is a forward-looking element in the setting of prices. Our formal tests, however, strongly reject the NK model.

The paper is in three further sections. In the first, after sketching the NK model, the test procedure of Galí and Gertler (1999) and some of its

[1] Mankiw (2001) argues that although the NK model 'has many virtues, it also has one striking vice: it is completely at odds with the facts' (pp. C52).

[2] This last test is similar in nature to Hall's (1978) test of the permanent income hypothesis - that consumption is a random walk. The difference is that the assumed stickiness of prices in the NK model implies that the lagged error-correction term and one lag in inflation will influence current inflation.

econometric difficulties, we show how the NK model can be interpreted as a forward-looking cointegrated model and how this feature can be exploited to derive a different set of tests. In section 3 we describe our data and report our results. We end with a summary.

2 Testing the NK Model

2.1 The NK model

Our theoretical framework is a conventional version of the NK model.[3] It assumes an economy consisting of a continuum of (identical) monopolistically competitive firms indexed by $j \in [0,1]$ each of which has a common, fixed probability, $1-\theta$, of resetting its price. θ is assumed to be independent of the time elapsed since the last adjustment and can be interpreted as a measure of price rigidity.[4] Those firms which reset their prices are assumed to do so to maximise their expected discounted profits subject to the constraints imposed by technology, the wage rate, and the possibility (defined by θ) that they may reset price at some future date. The resulting optimal price-setting rule is that each firm should set its price as a constant markup over a discounted stream of expected future nominal marginal costs. The lower the probability of it being able to reset its price, i.e. the higher the value of θ, the greater the weight the firm will place on expected future marginal costs. Formally, a logarithmic approximation to the optimizing rule is[5]

$$p_t^* = \log(\varphi) + (1-\beta\theta)\sum_{k=0}^{\infty}(\beta\theta)^k E_t MC_{t+k} \tag{1}$$

where p_t^* is the log of the price set by a firm which is resetting in period t; φ ($\equiv \frac{\phi}{\phi-1}$) is a firm's desired gross markup under flexible prices; ϕ is the price elasticity of demand for the firm's product; MC_{t+k} is the logarithm of the firm's nominal marginal costs in period $t+k$; β is a subjective discount factor; and E_t is the expectation operator conditional on information available at date t. The parameters ϕ and β are common to all firms. This equation can be written as

$$p_t^* = MC_t + \log(\varphi) + \sum_{k=1}^{\infty}(\beta\theta)^k E_t \Delta MC_{t+k} \tag{2}$$

[3] For a fuller derivation of the model see Galí and Gertler (1999), Sbordone (2001) and Woodford (1996).

[4] The assumption of a fixed probability of resetting, independent of the time since the previous adjustment, is due to Calvo (1983).

[5] See, for example, Gali *et al.* (2001) equation (7). This is the 'pure form' of the new-Keynesian model, in which equation (1) holds exactly. Later in the paper we relax this assumption and develop tests of a model which permits an 'optimisation error' to be added to equation (1).

The price level in period t is a weighted average of the prices set by those firms who reset in period t, p_t^*, and the prices of those firms who do not. Since, for each firm, the probability of resetting its price in period t is the same, and is assumed to be independent of the lapse in time since it last reset, the average price of those firms not resetting in period t will equal the average of all prices in period $t-1$. Since the proportion of firms not resetting each period is θ, the log of the actual price level, p_t, can be expressed as

$$p_t = (1-\theta)p_t^* + \theta p_{t-1} \tag{3}$$

From equations (1) and (3) one can derive an inflation equation of the form[6]

$$\pi_t = \lambda mc_t + \beta E_t \{\pi_{t+1}\} \tag{4}$$

where mc_t is the percentage deviation of the firm's real marginal cost from its steady state value; π_t is the inflation rate defined as $p_t - p_{t-1}$; and $\lambda = \frac{(1-\theta)(1-\beta\theta)}{\theta}$.

For our empirical work we shall follow Galí and Gertler (1999) and others by assuming a Cobb-Douglas technology. From this it is straightforward to derive MC_t as the log of unit labour costs plus a constant.[7]

2.2 GMM estimation of the NK model

A number of studies have used equation (4) to test the NK model. Galí and Gertler (1999), for example, using the log of labour income share, s_t, as their measure of real marginal costs, argue that, since under rational expectations the error in forecast of π_{t+1} is uncorrelated with information dated t and earlier, it follows from equation (4) that

$$E_t \{(\pi_t - \lambda s_t - \beta\pi_{t+1})z_t\} = 0 \tag{5}$$

where z_t is a vector of variables dated t and earlier (and are thus orthogonal to the inflation surprise in period $t+1$). This orthogonality condition forms the basis for estimation of the model via generalized method of moments (GMM). By substituting the expression for λ into equation (4) one can obtain an inflation equation which is non-linear in the structural parameters, θ and β. These can be estimated using a non-linear instrumental variables estimator.[8]

[6] See Galí and Gertler (1999) equation (10).

[7] Write $Y = AK^{\alpha_k}N^{\alpha_n}$ where Y, denotes output, A technology, K capital, and N labour. Then nominal marginal cost equals $W\frac{\partial N}{\partial Y}$ where W is the nominal wage rate. This equals $\frac{WN}{\alpha_n Y}$. Hence $MC = \log(\frac{WN}{Y}) - \log(\alpha_n)$.

[8] Galí, and Gertler (1999) use the same estimation procedure to estimate and test a model in which a proportion of firms are backward looking in that, when they reset their price, they set it to $p_{t-1}^* + \pi_{t-1}$. They estimate that approximately 25% of firms reset their prices in this way.

There are a number of econometric problems with this approach. First, as Galí and Gertler recognise, in small samples non-linear estimation using GMM can be sensitive to the way the orthogonality conditions are normalized. They themselves use two alternative specifications of the orthogonality condition as the basis for their GMM estimation and find some differences in parameter estimates as a result, though these differences are not marked.[9] Secondly, a failure to identify the set of relevant instruments may lead to residual serial correlation even under the null that the underlying model is true. These tests may therefore lead to a false rejection of the NK model on the grounds that it fails to explain inflation dynamics.

2.3 Cointegration-based tests of the NK model

Our test of the NK model bypasses these problems. From equation (2) it is clear that if MC_t is integrated of order 1, then p_t^* will also be integrated of order 1 and p_t^* and MC_t will be cointegrated with a cointegrating vector $[1\ -1]$. Hence the vector $x_t \equiv [MC_t\ p_t^*]'$ has an error-correction representation.[10]

$$B(L)\Delta x_t = -\gamma S_{t-1} + e_t$$

where $S_t \equiv p_t^* - MC_t$; $\Delta x_t = [\Delta MC_t\ \Delta p_t^*]'$; $B(L)$ is a two-by-two matrix polynomial in the lag operator of order $q-1$; γ is a column vector with two elements, at least one of which is non-zero; and e_t contains two white-noise error terms.

This error-correction representation implies that there must be Granger-causality from S_t to Δx_t. Intuitively, Granger-causality from S_t to ΔMC_t will be observed if firms have *extra* or *private* information about future changes in nominal marginal costs beyond the history of marginal costs itself. For example, consider a firm which, in period t, obtains private information that its marginal costs will increase at some time in the future by more than the history of its marginal costs would suggest. The firm cannot be certain that it will be able to reset its price in the period when this change in marginal costs actually occurs, so, if it gets the chance to do so in period t, it will reset its price above its *current* marginal costs by more than it otherwise would. Hence the difference between p_t^* and MC_t, which is S_t,

[9] The first takes the form, $E_t\left\{(\theta\pi_t - (1-\theta)(1-\beta\theta)s_t - \theta\beta\pi_{t+1})z_t\right\} = 0$ and the second, $E_t\left\{(\pi_t - \theta^{-1}(1-\beta\theta)s_t - \beta\pi_{t+1})z_t\right\} = 0$. They report various estimates of θ and β, which generally tell the same overall story. Defining US inflation in terms of the GDP deflator they estimate θ to be 0.83 using the first normalisation and 0.88 using the second. Using our data, described below, we find less sensitivity to the normalisation used: in the US case we derive estimates of θ of 0.904 (0.027) and 0.925 (0.035) for the two specifications; the corresponding parameters in the UK case are, respectively, 0.862 (0.045) and 0.881 (0.055). The numbers in brackets are estimated standard errors.

[10] See Campbell and Shiller (1988). Campbell (1987) used this framework to test the permanent income hypothesis of consumption.

will tend to be high and, if the firm's private information is correct, this high value of S_t will be followed by a rise in marginal costs that is higher than the history of marginal costs would suggest. Thus S_t will Granger-cause ΔMC_t and hence Δp_t^*.

This system can be re-arranged as the following q-order VAR in the vector $[\Delta MC_t \ S_t]'$

$$G(L)\begin{bmatrix} \Delta MC_t \\ S_t \end{bmatrix} = u_t \tag{6}$$

where $G(L)$ is a matrix polynomial of order q in which the coefficients on ΔMC_{t-q} are zero and u_t ($\equiv [u_{1t} \ u_{2t}]'$) is a vector of white-noise errors.

It is helpful to write (6) in the form

$$Z_t = AZ_{t-1} + v_t \tag{7}$$

where

$$Z_t = [\Delta MC_t, \ ... \ \Delta MC_{t-q+1}, \ S_t, \ ... \ S_{t-q+1}]'$$

$$v_t = [u_{1t}, 0, \ ..., \ 0, \ u_{2t}, \ 0, \ ..., \ 0]'$$

and A is the $2q \times 2q$ matrix[11]

$$A = \begin{bmatrix} \alpha_{111} & \alpha_{112} & ... & \alpha_{11q-1} & \alpha_{11q} & \alpha_{121} & \alpha_{122} & ... & \alpha_{12q-1} & \alpha_{12q} \\ 1 & 0 & ... & 0 & 0 & 0 & 0 & ... & 0 & 0 \\ \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & ... & 1 & 0 & 0 & 0 & ... & 0 & 0 \\ \alpha_{211} & \alpha_{212} & ... & \alpha_{21q-1} & \alpha_{21q} & \alpha_{221} & \alpha_{222} & ... & \alpha_{22q-1} & \alpha_{22q} \\ 0 & 0 & ... & 0 & 0 & 1 & 0 & ... & 0 & 0 \\ \vdots & \vdots & & \vdots & \vdots & \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & .. & 0 & 0 & 0 & 0 & ... & 1 & 0 \end{bmatrix}$$

It follows from (7) that we can write

$$E\left[Z_{t+k}|H_t\right] = A^k Z_t \tag{8}$$

where H_t is the firm's information set containing the current and lagged values of the variables in the VAR. Notice that, from the Granger-causality argument, S_t incorporates all information firms have about future movements in ΔMC_t which are not included in the history of ΔMC_t.

Equation (2) implies

$$S_t \equiv p_t^* - MC_t = \log(\varphi) + \sum_{k=1}^{\infty} (\beta\theta)^k E_t \Delta MC_{t+k}$$

[11] As noted above, the error-correction representation implies that in (7) $\alpha_{11q} = \alpha_{21q} = 0$.

Using this equation and equation (8) we can write:

$$\begin{aligned} S_t &= \log(\varphi) + \sum_{k=1}^{\infty} (\beta\theta)^k h' A^k Z_t \\ &= \log(\varphi) + h'\beta\theta A \left[I - \beta\theta A\right]^{-1} Z_t \end{aligned}$$

where $h = [1, 0, 0, ..., 0]'$.

Since, by definition, $S_t = g'Z_t$ where g' selects row $q+1$ of Z_t, it follows that the NK model implies the following set of restrictions on the A matrix[12]

$$g'[I - \beta\theta A] = h'\beta\theta A \tag{9}$$

which can be written $\alpha_{111} = -\alpha_{211}$, $\alpha_{112} = -\alpha_{212}$, $....\alpha_{11q} = -\alpha_{21q}$, and $1 - \beta\theta\alpha_{121} = \beta\theta\alpha_{221}$, $\alpha_{122} = -\alpha_{222}$, ... $\alpha_{12q} = -\alpha_{22q}$. So, one way to test the NK model is to estimate the parameters of (7), confirm/reject that S_t Granger-causes ΔMC_t, and test the set of restrictions shown in (9).

An alternative form of the test can be derived from first-differencing equation (3) to give the inflation equation

$$\pi_t = (1 - \theta)\Delta p_t^* + \theta\pi_{t-1}$$

Δp_t^* can be written as $\Delta MC_t + S_t - S_{t-1}$. From the VAR shown in (7) and the restrictions shown in (9), it follows that we can write inflation as

$$\pi_t = \frac{(1-\beta\theta)(1-\theta)}{\beta\theta} S_{t-1} + \theta\pi_{t-1} + (1-\theta)(u_{1t} + u_{2t}) \tag{10}$$

Inflation then, according to the NK model, should be a function of one-period lags in inflation itself and the error-correction term. Conditional on the presence of these two variables, further lags in inflation or any other lagged variables should be insignificant. A simple t-test (or F-test) of the significance for other variables in equation (10) provides an alternative test of the NK model. The influence of the error-correction term on inflation arises through its influence on nominal marginal costs. A high value for S_{t-1} implies that firms have extra information that marginal costs will rise at some time in the future. Firms who get the chance to reset their prices will reset at a higher price than they otherwise would in anticipation of this future rise in marginal costs. Initially the prices at which they reset will still be partly influenced by the current (low) level of marginal costs. As the time of the anticipated rise in marginal costs draws nearer, the influence of the current (low) level of marginal costs will tend to be lost and the influence of the anticipated (higher) marginal costs will dominate. So, all firms who reset their prices will be raising them. Thus when S_{t-1} is high, inflation will be higher than it otherwise would.

[12] When estimating the parameters in (7) we include constant terms but we ignore the additional restrictions this implies for (9).

Before we can carry out any of these tests we need to derive the error-correction term, S_t. Substituting for p_t^* in equation (3), using $S_t \equiv p_t^* - MC_t$, allows us to write

$$p_t = (1-\theta)MC_t + \theta p_{t-1} + (1-\theta)S_t \tag{11}$$

It is clear that *direct* knowledge of the value of θ would allow us to calculate S_t from equation (11). Alternatively, the value of θ could be *estimated* in a first-stage regression of equation (11) and the required S_t series derived as the residual from this regression divided by the estimated coefficient on MC_t.[13] Taylor (1999) reviewed the direct evidence on the frequency of price changes in the US and concluded that 'price changes and wage changes have about the same average frequency - about one year' (p.1020), implying a value of θ of around 0.75 in quarterly data. Hall *et al.* (1997), in a survey of 654 UK companies, found that in the year to September 1995 the median number of times that prices were changed was twice a year, which suggests a value of θ of 0.5.[14] We carried out tests of our model imposing these values of θ for US and UK, but, given that the evidence for these values, especially for the UK, cannot be regarded as anything like conclusive, we also carried out tests based on a first-stage estimate of θ from a regression of equation (11). As we report below, these regressions produced very similar estimates of θ for the two countries of around 0.75.[15]

The VAR shown in (7), the restrictions shown in (9), and equation (10) together suggest the following. First, the NK model can be tested by estimating the parameters in (7) and testing the set of restrictions given in (9); at the same time the implication that S_t should Granger-cause ΔMC_t can also be tested. Secondly, equation (10) implies that no terms other than S_{t-1} and π_{t-1} should appear in the inflation equation, and this can be tested using standard regression techniques. From an econometric perspective, the estimation of both the VAR system (7) or the single-equation (10) can be

[13] See Engle and Granger (1987).

[14] The Hall *et al.* sample substantially over-represents large firms, though the direction of bias this might introduce into the estimate of θ is not obvious.

[15] Equation (11) suggests that the cointegration relationship can also be estimated in the alternative form

$$MC_t = \frac{p_t - \theta p_{t-1}}{(1-\theta)} - S_t$$

though in this case the estimates of θ must be derived from a term involving the inverse of $1-\theta$. Our estimates of θ thus derived were noticeably lower (0.3 for the UK and 0.6 for the US) than Taylor's (1999) estimate for the US. So, in what follows, we concentrate on the S series derived from equation (11). However, we also carried out all our subsequent tests using estimates of θ and S derived from the regression of the cointegrating equation in its alternative form. We also carried out our tests using estimates of the cointegrating relationship in its two 'restricted' forms: $p_t - MC_t = \theta(p_{t-1} - MC_t) + (1-\theta)S_t$; and $MC_t - p_{t-1} = \frac{\Delta p_t}{1-\theta} - S_t$. The results obtained were so similar to those based on their unrestricted equivalents that we do not report them.

achieved without the need to identify relevant instrumental variables for inflationary expectations; under our approach firms' expectations are fully captured by movements in S (and ΔMC).

2.4 Optimising errors

The test procedures we have outlined are based on the 'pure form' of the NK model - one in which equations (1) and (2) are assumed to hold exactly. To allow for 'errors in optimisation', we relax this assumption and write equation (2) as

$$p_t^* = MC_t + \log(\varphi) + \sum_{k=1}^{\infty} (\beta\theta)^k E_t \Delta MC_{t+k} + \omega_t$$

where ω_t is the optimisation error. The expression for S is then

$$S_t \equiv p_t^* - MC_t = \log(\varphi) + \sum_{k=1}^{\infty} (\beta\theta)^k E_t \Delta MC_{t+k} + \omega_t \tag{12}$$

Lagging equation (12) by one period , dividing by $\beta\theta$ and subtracting from equation (12)

$$\begin{aligned} S_t - \frac{S_{t-1}}{\beta\theta} &= \frac{\log(\varphi)\,(\beta\theta - 1)}{\beta\theta} + \frac{1}{\beta\theta} \sum_{k=1}^{\infty} (\beta\theta)^k\, \Delta E_t \Delta MC_{t+k} \\ &\quad - E_{t-1} \Delta MC_t + \omega_t - \frac{\omega_{t-1}}{\beta\theta} \end{aligned}$$

where $\Delta E_t \Delta MC_{t+k} \equiv E_t \Delta MC_{t+k} - E_{t-1} \Delta MC_{t+k}$ (the revision in expectations as more information becomes available between period $t-1$ and t). Add ΔMC_t to this expression

$$\begin{aligned} S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t &= \frac{\log(\varphi)\,(\beta\theta - 1)}{\beta\theta} + \\ &\quad \frac{1}{\beta\theta} \sum_{k=0}^{\infty} (\beta\theta)^k\, \Delta E_t \Delta MC_{t+k} + \omega_t - \frac{\omega_{t-1}}{\beta\theta} \end{aligned} \tag{13}$$

Since $\Delta E_t \Delta MC_{t+k}$ must be uncorrelated with all information dated $t-1$ and earlier, we can re-write equation (13) as

$$S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t = \delta_0 + \varepsilon_t + \omega_t - \frac{\omega_{t-1}}{\beta\theta} \tag{14}$$

where $\delta_0 \equiv \frac{\log(\varphi)(\beta\theta - 1)}{\beta\theta}$ and where $\varepsilon_t \left(\equiv \frac{1}{\beta\theta} \sum_{k=0}^{\infty} (\beta\theta)^k\, \Delta E_t \Delta MC_{t+k} \right)$ is uncorrelated with all variables dated $t-1$ and earlier.[16] Re-parameterising the error terms in equation (14)[17]

$$S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t = \delta_0 + \eta_t - \kappa\eta_{t-1} \tag{15}$$

[16] With no measurement error ($\omega_t = 0$, for all t), equation (14) is implied by the restrictions of the 'pure form' NK model, with $\varepsilon_t \equiv u_{1t} + u_{2t}$.

[17] See Hamilton (1994, pp. 102-107).

where the variance of η_t and the parameter κ are functions of the variances of the separate shocks (ε_t and ω_t) and $\beta\theta$. As long as the optimising error is orthogonal to all lagged information[18] (including its own lagged value), the NK model implies that $S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t$ would be uncorrelated with all information dated $t-2$ and earlier.[19] This feature of the model will form the basis of our test of a model which allows for optimisation errors. In the next section we carry out our tests of the NK model using UK and US data.

3 Empirical results

3.1 Data

Our data, full details of which are given in Appendix A, are from the UK and the US and cover the private (non-government) sector.[20] We adopt (for both countries) data definitions similar to those employed by Batini, Jackson and Nickell (2000). The data are quarterly and seasonally adjusted covering 1963Q2-2000Q4 in the UK and 1960Q1-2000Q4 in the US. In the UK case the inflation rate is defined as the quarterly change in the log of the overall GDP price deflator[21] and in the US the inflation rate is based on the non-government GDP deflator. As explained earlier, the assumption of Cobb-Douglas technology allows us to measure ΔMC by the change in the log of unit labour costs. A series for unit labour costs was constructed for both countries by taking the ratio of nominal non-government compensation of employees to real non-government GDP. In both cases we adjust the published compensation estimates to include a labour income component of the income of self-employed (UK) or proprietors (US).[22]

[18] This is a natural identifying assumption for the optimising error. It is directly analagous to the treatment of 'transitory consumption' in empirical models of the permanant income model (see Campbell (1987)).

[19] The NK model with optimisation errors implies a different set of restrictions on the VAR model in S and ΔMC. In this case equation (9) becomes

$$g'A[I - \beta\theta A] = h'\beta\theta A^2$$

These restrictions are highly non-linear and not easily implemented empirically. We therefore adopted the procedure described in the text.

[20] Galí and Gertler's (1999) study of US inflation measured the share of labour in the non-farm business sector, though their measure of inflation was based on the overall GDP deflator. Tests of our model using unit labour costs for the non-farm business sector are very similar to those we report below. We prefer the wider coverage to enable direct comparison with the UK.

[21] The prices are basic prices for the UK and market prices for the US. As Batini *et al* point out, the use of basic prices means that value added is measured *net of indirect taxes*, which is theoretically more appropriate than measures in market prices. It was not possible to construct the non-government GDP deflator in the UK case due to the lack of a constant price government value added series.

[22] This procedure is adopted by Batini, Jackson and Nickell (2000). It has been used in other contexts when calculating aggregate labour income (see for example Blinder and

The adjustment we make to employee compensation implies that the average return to labour of the self-employed/proprietors is equal to the average remuneration of employees in employment. Self-employment income is not separately identified in the UK accounts[23] so we follow the procedure used by Batini, Jackson and Nickell (2000), who adjust compensation by the ratio of total employment to the number of employees. The imputation of labour income of proprietors/self employed is particularly important given the growing importance of these sectors, especially in the UK, where the proportion of self-employment to total employment rose from around 8% in 1960 to 13% in 2000.

The means of π and ΔMC in the US are respectively 3.62% per annum and 3.79% per annum with standard deviations 2.57% and 3.77%. In the UK the respective means of π and ΔMC are 6.66% per annum and 6.73% per annum with standard deviations 5.78% and 7.45%. We graph the series for ΔMC and π in Figures 1 and 2. Under our assumption of Cobb-Douglas technology the two series should move perfectly together if prices were fully flexible, whereas the inability of firms to change prices instantly in the NK model will inject some smoothness into prices. For both countries the graphs are enough to reject the flexible price model and establish some *prima facie* case for the NK model.

For both countries ADF tests establish that p and MC are clearly not $I(0)$. In the case of the UK we can reject a unit root in π and ΔMC: the ADF test statistics are -2.91 and -4.03 (respectively) which are significant at the 5% level (for preferred lags of 1 in each case).[24] The ADF test statistic for the error-correction term, S, is -3.44 with one lag term.[25] For the US, ΔMC is clearly $I(0)$ with an ADF test statistic of -4.96 with one lag, and so is S with an ADF test statistic of -4.469 (no lags). The stationarity of π is less clear. We obtain ADF test statistics of -2.36 (4 lags) for π, which compares with critical values of -2.89 and -2.58 at the 5% and 10% significance levels.[26] Given the marginal nature of this result, we applied to this series the KPSS test[27] in which the null hypothesis is that the variable is stationary about a constant level. We obtained a test statistic of 0.379 (assuming a lag truncation parameter of 8), which compares with a critical value of 0.463 at the 5% level. The null hypothesis of stationarity is therefore not rejected for US inflation.[28] We proceed then on the assumption that,

Deaton (1985)).

[23] The income of the self-employed is now consolidated with other incomes in an 'Other Income' category.

[24] The lag length was determined by truncating at the last significant t-statistic.

[25] A second lag, whose significance is marginal, produced an ADF statistic of -2.61, which lies between the 5% and 10% critical values.

[26] A measure of US inflation based on the overall GDP deflator has similar properties.

[27] See Kwiatkowski, Phillips, Schmidt and Shin (1992).

[28] Recent research has found that US inflation is a fractionally-integrated (long-memory) stationary process. See for example Bekdache and Baum (2000), Hassler and Wolters

for both countries, MC and p are cointegrated of order (1,1) and that MC and the unobserved p^* are similarly cointegrated.[29]

3.2 Results of conventional tests

We begin by reporting, in Table 1, the results of estimating the structural parameters of equation (4) by GMM. We also report, for comparative purposes, the parameter estimates derived by Galí and Gertler (1999).[30] The results are based on the orthogonality conditions given by equation (5) and the results reported in the last two columns of the table are based on the following instrument set: two lags in the labour share, the output gap and wage inflation and four lags in inflation.

The point-estimates of θ are all on the high side, implying average price contracts of 8.6 (Galí and Gertler) and 13.4 quarters for the US and 8.4 in the UK case. Our point-estimate of β for the UK is greater than one. Our estimate of β for the US suggests a discount factor of 2.5% per quarter; Galí and Gertler's suggests a discount factor of 6.3% per quarter. Both estimates are noticeably higher than the conventional assumption of a discount factor for these countries over this period of 1-2% per quarter.

One feature of the results presented in Table 1 is the substantial residual serial correlation associated with all the estimated equations: the Ljung-Box portmanteau test[31] for fourth-order serial correlation emphatically rejects white-noise errors in all cases. This is the key reason for rejecting the NK model that emerges from this approach. In both countries there appears to be substantially greater serial correlation in inflation than the NK model can account for.

3.3 Results of cointegration-based tests

Our estimates of equation (11), the cointegrating equation for each country, are

$$\begin{aligned} UK \quad &: \quad p_t = \underset{(0.0115)}{0.1159} + \underset{(0.0286)}{0.7383} p_{t-1} + \underset{(0.0289)}{0.2605} MC_t \\ \sigma \quad &= \quad 0.0113 \quad DW = 0.7412 \end{aligned}$$

(1994, 1995) and Baillie, Chung and Tieslau (1996).

[29] For the UK, all the other methods of deriving the S series described in footnote (15) suggested, at the 10% level, that MC and p are cointegrated. For the US the evidence was less clear: it was not possible to reject, at the 10% level, the hypothesis of non-stationarity in the S series derived from estimates of the 'restricted' cointegration equation.

[30] We are grateful to Galí and Gertler for providing us with their data.

[31] The Ljung-Box statistic is strictly valid only when testing for residual serial correlation in $ARIMA$ models (see Davidson and MacKinnon (1993) p.364) so the p-values we report should be considered as approximations.

$$\begin{aligned} US \quad &: \quad p_t = \underset{(0.0074)}{0.1387} + \underset{(0.0150)}{0.7335} p_{t-1} + \underset{(0.0147)}{0.2603} MC_t \\ \sigma \quad &= \quad 0.0037 \quad DW = 0.4959 \end{aligned}$$

The sum of the coefficients on p_{t-1} and MC_t should be unity and the coefficient on p_{t-1} defines the proportion of firms not re-setting each period. In the US case the sum of the coefficients is 0.994 and in the UK case it is 0.999. There is also a noticeable similarity in the parameter estimates derived from the two data-sets: in both countries the average duration of prices implied by these estimates is around 4 quarters, in line with the direct evidence for the US surveyed by Taylor (1999). The residuals from these two equations and their respective estimates of $1-\theta$ were used to provide our measure of S_t.

We begin with the 'pure form' of the NK model - one that assumes exact optimisation on the part of firms. To test the restrictions of the model we need first to determine the appropriate order of A. To do so, we first impose on the A matrix the two restrictions $\alpha_{11q} = \alpha_{21q} = 0$ and then determine q using the Akaike Information Criterion (AIC). Specifically, we computed the AIC for a series of VARs in which, q, the order of the lag on S_t, was one more than the order of the lag on ΔMC_t. We considered values of q from 2 to 12. This procedure suggested $q = 4$ for the UK and 3 for the US.[32]

Table 2 presents maximum likelihood estimates of the key parameters of the relevant rows of A (rows 1 and $q+1$), imposing the cross-equation restrictions shown in (9).[33] There are two sets of results for each country: in one the combined coefficient $\beta\theta$ is estimated; in the other we impose a 'plausible' value of 0.98 for β which allows us to estimate θ; this in turn allows us to test the hypothesis that the value of θ estimated from the VAR is equal to $\widetilde{\theta}$, the estimate of θ from the first-stage regression of equation (11). To check that our results were not highly sensitive to our selection of q, we show in Table 2 the results obtained when assuming values of q from 3 to 5 inclusive. Table 3 presents estimates of equation (10) for both countries plus associated test statistics of the null hypothesis that the coefficients on variables other than S_{t-1} and π_{t-1} are individually or jointly insignificant.

The results in the two tables taken together suggest the following. The estimates of α_{121} (the coefficient on S_{t-1} in the ΔMC_t equation) and the estimates of $\sum_{j=1}^{q} \alpha_{12j}$ are consistently positive and generally significant. (In the unrestricted VARs the estimates of α_{121} were all positive and highly significant.[34]) This provides strong support for the prediction of the model

[32]For both countries the Box-Ljung test for residual serial correlation in the unrestricted VARs suggests that we cannot reject white noise errors in either equation at conventional significance levels.

[33]The variables in the VAR were de-meaned prior to estimation.

[34]This was also true of the unrestricted VARs based on the different methods of estimating the S series described above.

that S_t Granger-causes ΔMC_t and that therefore in both countries there is a forward-looking element to the setting of prices. However, the NK model is strongly rejected by the formal tests. The statistics given in the row labelled $p(LR)$ in Table 2 show the p-values associated with a likelihood ratio test of the set of restrictions (9). They all indicate that these restrictions are emphatically rejected for both countries. Furthermore, where we could estimate θ from the VAR, we could always reject the null hypothesis that it equalled $\widetilde{\theta}$. In general, the results in Table 2 suggest that the point estimates of θ are implausibly high.

The results in Table 3 confirm this rejection of the model. Whilst the estimates of θ are now more reasonable, the estimates of β are highly erratic, and often imply a negative coefficient on S_{t-1}, contrary to the model's predictions. Furthermore there is strong evidence from the t-tests and F-tests that variables other than S_{t-1} and π_{t-1} are significant influences on inflation. In particular, inflation lagged two quarters is highly significant in both countries.[35]

We report in Table 4 tests of the NK model allowing for optimisation errors. Under the null hypothesis that the model is true, the variable $S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t$ should be orthogonal to all information dated $t-2$ and earlier. To contruct this variable, we assume that $\beta\theta = 0.98\widetilde{\theta}$. Also under the null, $S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t$ should follow an $MA(1)$ process, though the parameters of this process will depend on the relative variances of ε_t and ω_t.[36] We therefore estimate (15) allowing for a first-order moving average error process[37] and we add to this equation a selection of lagged terms in S and ΔMC. The restrictions implied by the NK model are clearly rejected: the lagged terms in S and ΔMC are significantly different from zero, and a likelihood ratio test of the joint significance of the lagged terms is highly significant.

Overall, our results confirm the general finding of others: that without modification the NK model - with or without optimising errors - can be decisively rejected.

There are a number of possible points of weakness in the NK model. First, firms may not be forward looking in their price-setting behaviour: Galí and Gertler (1999) modify the NK model by allowing for a proportion of 'backward-looking' firms who base their prices on the recent behaviour of their 'forward-looking' competitors. In the absence of any explanation of why some firms are backward-looking and some forward-looking, this modification to the NK model inevitably appears somewhat contrived. Further-

[35] These results were qualitatively unchanged when our alternative estimates of θ and S were employed.

[36] If the variance of ω_t were relatively small compared with that of ε_t, the estimated κ could well be close to zero.

[37] We use a maximum likelihood algorithm proposed by Ansely (1979) and implemented in GAUSS's ARIMA Time Series appplication.

more their own estimate of the fraction of firms who are backward-looking is very sensitive to the normalisation procedure required for GMM estimation, with some estimates as low as 8% and others as high as 50%; and our own finding that the error-correction term strongly Granger-causes marginal costs indicates that there is a strong element of forward-looking behaviour.

A second potential weakness, explored in Demery and Duck (2001), is the assumption that firms have full information when forming expectations of future costs. They develop a NK model in which each firm's marginal costs have idiosyncratic and common components, and each firm faces the problem of distinguishing the two. They show that, if the acquisition of information is costly, firms may optimally choose to solve this information problem imperfectly and that this can significantly alter inflation dynamics. In their model firms are all forward-looking. They find that the restrictions imposed by this amended NK model cannot be rejected on the UK and US data-sets we use in this paper.

A final potential weakness of the model, which has not been explored, is that, in following Calvo (1983), it assumes that the price re-setting probability is independent of the time elapsed since they were last set. This assumption guarantees that no lags in the price level beyond one appear in equation (3). It would seem more realistic to assume that those firms which re-set most recently are the least likely to reset in the current period.

4 Conclusions

We have proposed a method of testing the NK model of inflation that exploits the long-run relationship between prices and marginal costs implied by the model. Its main advantage is that it allows us to model firms' expectations about marginal costs in a very simple VAR framework and, as a result, to develop a relatively simple set of formal tests which bypasses a number of econometric problems encountered in other approaches. Our tests confirm the results of other studies that, for the UK and US, the NK model can be formally rejected. However they also provide strong evidence that there is a forward-looking component to price setting as the NK model suggests.

Table 1 GMM estimates of equation (4)

	United States		United Kingdom
	Galí and Gertler (1999)	D&D data	D&D data
θ	0.884	0.925	0.881
	(0.020)	(0.035)	(0.055)
β	0.942	0.976	1.046
	(0.018)	(0.026)	(0.038)
λ	0.022	0.008	0.011
	(0.008)	(0.008)	(0.013)
$Q(4)$	0.0058	0.0014	0.0000

Notes: Estimated standard errors in (.)
$Q(n)$: p-value of the Ljung Box test for nth order residual serial correlation.

Table 2 Estimates of Restricted VAR

	UK $\widetilde{\theta} = 0.7383$			US $\widetilde{\theta} = 0.7335$		
	$q = 3$	$q = 4$	$q = 5$	$q = 3$	$q = 4$	$q = 5$
			$\beta\theta$ estimated			
α_{121}	0.248	0.262	0.271	0.279	0.294	0.282
	(0.035)	(0.035)	(0.036)	(0.060)	(0.061)	(0.063)
$\sum_{j=1}^{q} \alpha_{12j}$	0.110	0.079	0.087	0.195	0.197	0.184
	(0.036)	(0.037)	(0.039)	(0.050)	(0.053)	(0.057)
$\beta\theta$	1.143	1.141	1.096	0.979	0.976	0.983
	(0.096)	(0.093)	(0.085)	(0.063)	(0.063)	(0.064)
$p(LR)$	0.000	0.000	0.000	0.000	0.000	0.000
			$\beta = 0.98$			
θ	1.166	1.165	1.118	0.999	0.996	1.004
	(0.098)	(0.094)	(0.087)	(0.064)	(0.064)	(0.065)
$p(\theta = \widetilde{\theta})$	0.000	0.000	0.000	0.000	0.000	0.000

Additional notes: $p(LR)$: p-value of the likelihood ratio test of model's restrictions.
$p(\theta = \widetilde{\theta})$: p-value of the 't' test of the null hypothesis that the (VAR) estimated value of θ equals $\widetilde{\theta}$.

Table 3 Tests using inflation equation (10)

	UK			US		
β	2.352	1.981	2.831	-3.261	1.632	1.620
	(2.370)	(0.260)	(0.902)	(19.456)	(0.139)	(0.146)
θ	0.868	0.554	0.363	0.960	0.749	0.696
	(0.090)	(0.109)	(0.130)	(0.046)	(0.081)	(0.102)
π_{t-2}	-	0.352	0.250	-	0.227	0.202
		(0.077)	(0.088)		(0.075)	(0.080)
ΔMC_{t-1}	-	-	0.150	-	-	0.021
			(0.064)			(0.035)
ΔMC_{t-2}	-	-	0.089	-	-	0.042
			(0.061)			(0.033)
σ	0.010	0.009	0.009	0.003	0.003	0.003
R^2	0.524	0.582	0.600	0.806	0.817	0.819
$Q(12)$	0.003	0.651	0.556	0.171	0.350	0.235
$p(F)$	-	-	0.000	-	-	0.016

Additional notes: σ: equation standard error
$p(F)$: p-value of F-test of joint significance of additional variables.

Table 4 Tests using equation (15)

$$S_t - \frac{S_{t-1}}{\beta\theta} + \Delta MC_t = \delta_0 + \sum_{i=2}^{q} \delta_{i-1}\Delta MC_{t-i} + \sum_{i=2}^{q} \delta_{q+i-2}S_{t-i} + \eta_t - \kappa\eta_{t-1}$$

	UK			US		
	$q=3$	$q=4$	$q=5$	$q=3$	$q=4$	$q=5$
$\sum_{i=2}^{q} \delta_{i-1}$	0.714	0.706	0.678	0.662	0.697	0.779
	(0.128)	(0.126)	(0.133)	(0.099)	(0.102)	(0.104)
$\sum_{i=2}^{q} \delta_{q+i-2}$	-0.338	-0.347	-0.332	-0.343	-0.365	-0.424
	(0.046)	(0.045)	(0.049)	(0.056)	(0.058)	(0.060)
κ	0.639	0.660	0.613	0.334	0.355	0.353
	(0.085)	(0.090)	(0.088)	(0.085)	(0.088)	(0.088)
$p(LR)$	0.000	0.000	0.000	0.000	0.000	0.000

Additional notes: $p(LR)$: p-value of likelihood ratio test of the joint significance of additional variables.

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4.1 Appendix A The Data

The raw data used in this paper can be downloaded from the following University of Bristol web site:

http://www.ecn.bris.ac.uk/www/ecdd/newk/newk.htm

4.1.1 Data Definitions for the UK

UK data were retrieved from the National Statistics DataBank Online at http://www.data-archive.ac.uk/. The four-digit codes are the relevant National Statistics codes for the series used.

π is the inflation rate defined as the first difference in the logarithm of the GDP deflator: $\pi_t = \log(DEF_t) - \log(DEF_{t-1})$, where $DEF = \frac{\text{ABML}}{\text{ABMM}}$, ABML is Gross Value Added (average) in current basic prices, seasonally adjusted; and ABMM is Gross Value Added in 1995 basic prices, seasonally adjusted.

The log of real marginal costs ($MC_t - p_t$) or equivalently the log of the share of labour is defined as:

$$MC_t - p_t = \log\left[\frac{(\text{DTWM–NMXS}^a)\left(\frac{\text{DYZN+BCAJ}}{\text{BCAJ}}\right)}{\text{ABML-NMXV}^a\text{-NMXS}^a}\right]$$

where DTWM is total compensation of employees (£m) seasonally adjusted; NMXS^a is the variable NMXS seasonally-adjusted (X11), where NMXS is compensation of employees in government seasonally unadjusted; similarly NMXV^a is the variable NMXV seasonally-adjusted, where NMXV is general government gross operating surplus; DYZN is the number of self-employed workforce jobs (000, seasonally adjusted); and BCAJ is the number of employee workforce jobs (000, seasonally adjusted). Prior to 1978, the two employment series were available for the second quarter in each year only, so for these years observations for other quarters were derived by linear interpolation. This definition of labour share follows the preferred definition adopted by Batini, Jackson and Nickell (2000).

The logarithm of nominal marginal cost (MC) is defined as:

$$MC = \log\left[\frac{(\text{DTWM–NMXS}^a)\left(\frac{\text{DYZN+BCAJ}}{\text{BCAJ}}\right)}{\text{ABMM-}\left(\frac{\text{NMXV}^a\text{+NMXS}^a}{DEF}\right)}\right]$$

where, in the absence of a constant price series for government value added, we have assumed that the government value added deflator is the same as that for Gross Value Added. The growth in nominal marginal costs is defined as: $\Delta MC_t \equiv MC_t - MC_{t-1}$.

Real output (y) is ABMM, gross value added in 1995 basic prices, seasonally adjusted. The wage rate is defined as:

$$W = \frac{\text{DTWM}\left(\frac{\text{DYZN+BCAJ}}{\text{BCAJ}}\right)}{\text{DYZN+BCAJ}}$$

and wage inflation is defined as $\Delta w_t = \log(W_t) - \log(W_{t-1})$.

4.1.2 Data Definitions for the US

US data were obtained from:

- the US Bureau of Labor Statistics web site: http://stats.bls.gov/
- the Bureau of Economic Analysis web site: http://www.bea.doc.gov/.

All variables are seasonally adjusted and (where appropriate) at annual rates.

π is the inflation rate defined as the first difference in the logarithm of the non-government GDP deflator: $\pi_t = \log(DEF_t) - \log(DEF_{t-1})$, where $DEF = \frac{PY-PYG}{Y-YG}$, PY is GDP in current prices (\$b), PYG is General Government GDP (\$b), Y is GDP in billions of chained (1996) dollars (\$b) and YG is General Government GDP in billions of chained (1996) dollars (\$b).

The log of real marginal costs ($MC_t - p_t$) or equivalently the log of the share of labour is defined as:

$$MC_t - p_t = \log\left[\frac{COMP - COMPG}{PY - PYG - PROP}\right]$$

where: $COMP$ is total compensation of employees (\$b); $COMPG$ is government compensation of employees (\$b) and $PROP$ is proprietor's income (with inventory valuation and capital consumption adjustments (\$b).

The logarithm of nominal marginal cost (MC) is defined as:

$$MC = \log\left[\frac{COMP - COMPG + \left(\frac{COMP-COMPG}{PY-PYG-PROP}\right)PROP}{Y - YG}\right]$$

The growth in nominal marginal costs is defined as: $\Delta MC_t \equiv MC_t - MC_{t-1}$.

Real output (y) is $Y - YG$. The wage rate is defined as:

$$W = \frac{COMP - COMPG + \left(\frac{COMP-COMPG}{PY-PYG-PROP}\right)PROP}{L - LG}$$

where L and LG are (respectively) total and government employment (000) and wage inflation is defined as $\Delta w_t = \log(W_t) - \log(W_{t-1})$.

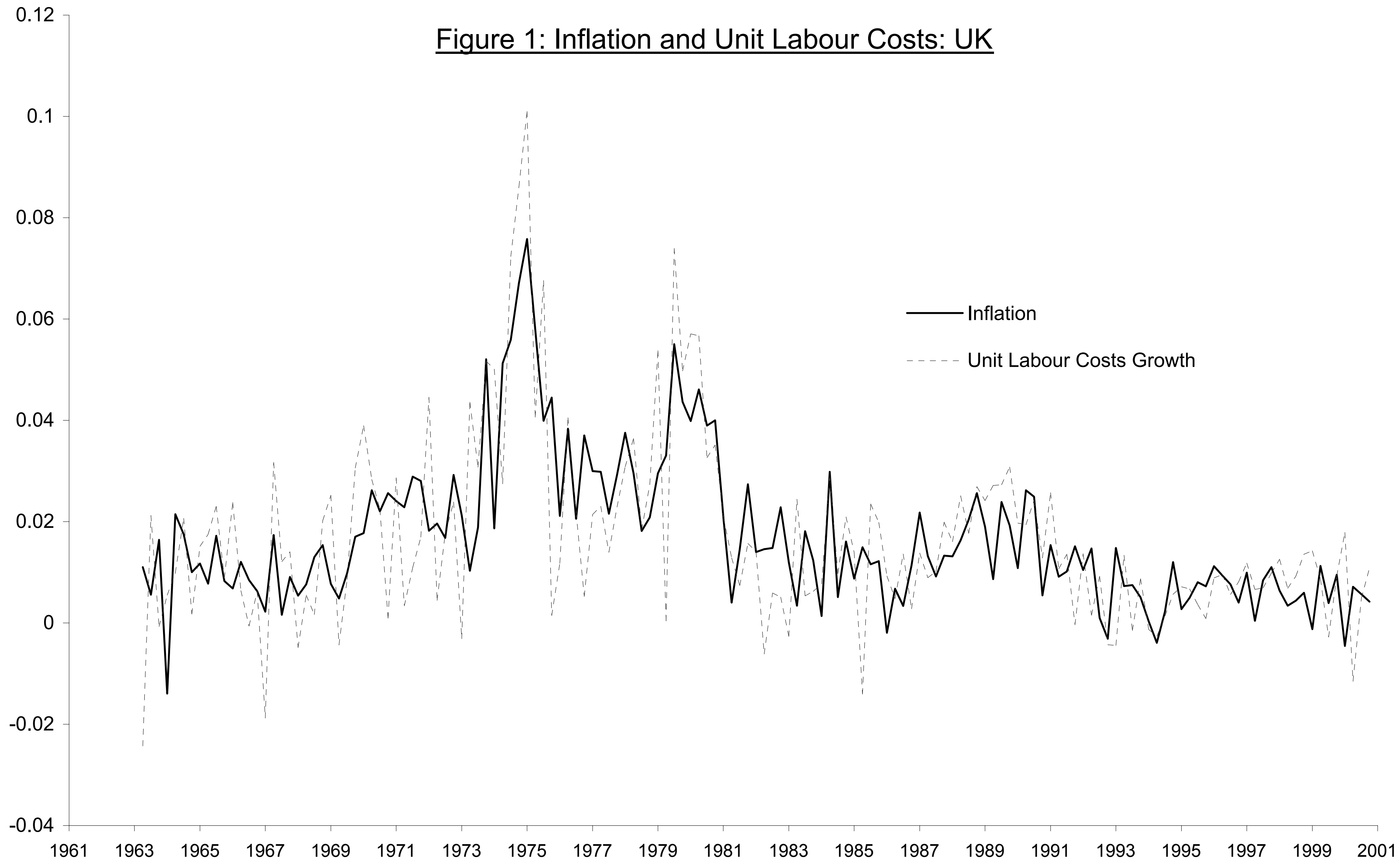
Figure 1: Inflation and Unit Labour Costs: UK
Inflation
Unit Labour Costs Growth
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001

Figure 2: Inflation and Unit Labour Costs: US