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# Second-Order Approximation to the Rotemberg Model around a Distorted Steady State*

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## ABSTRACT

Less is known about social welfare objectives when it is costly to change prices, as in Rotemberg (1982), compared with Calvo-type models. We derive a quadratic approximate welfare function around a distorted steady state for the costly price adjustment model. We highlight the similarities and differences to the Calvo setup. Both models imply inflation and output stabilization goals. It is explained why the degree of distortion in the economy influences inflation aversion in the Rotemberg framework in a way that differs from the Calvo setup.

**JEL Classification:** E52, E61, E63.
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## 1. Introduction

Dynamic stochastic general equilibrium (DSGE) models incorporating sticky prices often adopt the Calvo (1983) device that each period firms face a constant probability of being able to reset price. The resulting framework's popularity is partly explained by nice features of its linear-quadratic approximation. In particular, the first-order approximation to firms' price setting behavior implies a Phillips relation with fairly sharp empirical implications for the equilibrium relationship between output and inflation. Moreover, the second-order approximation to the social welfare function provides a rigorous justification for a focus *predominantly* on inflation in the conduct of monetary policy.[1]

An alternative approach is developed in Rotemberg (1982) based on the simple idea that changing prices is costly. This approach is related to the $sS$ literature. But as the cost of price adjustment grows in the square of price changes, Rotemberg's approach is simpler and somewhat easier to incorporate in DSGE models.

A key feature of the Rotemberg model is that all firms change prices in unison; there is no price dispersion as in Calvo's approach. That makes for algebraic simplicity but also implies that the costs of inflation are somewhat different across the two models. In particular, inflation is generally much more costly in Calvo's framework. For example, Damjanovic and Nolan (2008, 2010) compare the seigniorage-maximizing inflation rates (SMIRs) across models and find that the Rotemberg-based SMIR is generally in double digits and close to the flexible price SMIR . Under Calvo the SMIR is in single figures and perhaps as low as $2 - 3\%$. That is because price dispersion distorts substantially labour supply and demand decisions in Calvo's model. In Rotemberg's model inflation predominantly affects

[1] Benigno and Woodford (2005) is a detailed analysis of the framework to which we refer.

the economy through the direct cost of price adjustment.[2]

The differing impact of inflation across models raises the issue of how (monetary) policy objectives might differ between frameworks. This paper shows that, in fact, the linear-quadratic approximation to a baseline Rotemberg model around a distorted, zero-inflation steady state is almost equivalent to the Calvo model. In particular, the second-order approximation to social welfare has the same form and, more surprisingly, very similar coefficients attached to inflationary and output gaps as in the Calvo model. However, in the Rotemberg model the social weight on inflation objectives is more sensitive to the degree of inefficiency in the economy because agents ultimately endogenize some important costs of inflation that agents in the Calvo model cannot.

Section 2 sets out agents' decisions and Section 3 looks at firms' decisions. In Section 4 a Ramsey problem is constructed to characterize the optimal steady state around which the approximations will take place. Section 5 describes the second-order approximation (additional manipulations are in the appendix) and describes our key results.

## 2. Agent's decisions

There are a large number of identical agents in the economy who evaluate utility with the following criterion:

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t) = E_0 \sum_{t=0}^{\infty} \beta^t \left( \log(C_t) - \frac{\lambda}{1+v} N_t^{1+v} \right). \tag{2.1}$$

$E_t$ denotes the expectations operator at time $t$, $\beta$ is the discount factor, $C_t$ is consumption and $N_t$ is the quantity of labour supplied, $v \geq 0$ measures labour supply elasticity while $\lambda$ is a 'preference' parameter. Consumption is defined over a

[2] Ascari and Rossi (2008) compare these two models and find that they behave differently with trend inflation.

basket of goods of measure one and indexed by $i$, $C_t = \left[\int_0^1 c_t(i)^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}}$. The price-level, $P_t$, is $P_t = \left[\int_0^1 p_t(i)^{1-\theta} di\right]^{\frac{1}{1-\theta}}$. The demand for each good is $Y_t(i) = \left(\frac{p_t(i)}{P_t}\right)^{-\theta} Y_t^d$, where $p_t(i)$ is the nominal price of the final good produced in industry $i$ and $Y_t^d$ denotes aggregate demand.

Agents face the flow budget constraint

$$C_t + B_t = \frac{[1+i_{t-1}]}{\pi_t} B_{t-1} + w_t N_t + \Pi_t. \tag{2.2}$$

As all agents are identical, the only financial assets traded will be government bonds. Here $B_t$ denotes the nominal value at the end of date $t$ of government bond holdings, $1 + i_t$ is the nominal interest rate on this 'riskless' bond, $w_t$ is the real wage, and $\Pi_t$ is remitted profits. Agents maximize (2.1) subject to (2.2). Necessary conditions for an optimum include the labour supply function (2.3) and the consumption Euler equation, (2.4):

$$\lambda N_t^v C_t = w_t; \tag{2.3}$$

$$E_t \left\{ \beta \frac{C_t}{C_{t+1}} \frac{1}{\pi_{t+1}} \right\} = \frac{1}{1+i_t}. \tag{2.4}$$

## 3. Firm's decisions

Labour is the only factor of production. Firms are monopolistic competitors who produce their distinctive goods according to the following technology

$$Y_t(i) = A_t N_t(i)^{1/\phi}, \tag{3.1}$$

where $N_t(i)$ denotes labour hired by firm $i$ and $A_t$ is a productivity shifter. There are diminishing returns to labour, $\phi > 1$. The demand for output determines the demand for labour, so

$$N_t(i) = \left(\frac{Y_t(i)}{A_t}\right)^{\phi} = \left(\frac{P_t(i)}{P_t}\right)^{-\theta\phi} \left(\frac{Y_t}{A_t}\right)^{\phi}. \tag{3.2}$$

Following Rotemberg (1982), Schmitt-Grohe and Uribe (2004) and Bouakez et al. (2009), it is costly for firms to change prices:

$$\text{Price adjustment cost} = \frac{\xi}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - 1\right)^2,$$

where $\xi > 0$ is a measure of price stickiness.

The firm sets its price to maximize the net present value of future profits:

$$\max E_t \sum_{k=0}^{\infty} d_{t,t+k} \left( Y_{t+k} \left( \frac{P_{t+k}(i)}{P_{t+k}} \right)^{1-\theta} - \mu_{t+k} w_{t+k}(i) N_{t+k}(i) - \frac{\xi}{2} \left( \frac{P_{t+k}(i)}{P_{t+k-1}(i)} - 1 \right)^2 \right).$$

Here $d_{t,t+k} := \beta^{t+k} \left( C_t / C_{t+k} \right)$and $\mu_{t+k}$represents cost-push factors (including labour taxation, perhaps). The first-order condition with respect to $\frac{P_t(i)}{P_t}$ is derived and, since all firms charge the same price, in equilibrium $\frac{P_t(i)}{P_t} = 1$. The Phillips relation is readily derived:

$$(\theta - 1) Y_t - \theta \phi \mu_t w_t A_t^{-\phi} Y_t^{\phi} + \xi \pi_t (\pi_t - 1) = E_t \beta \frac{C_t}{C_{t+1}} \xi \pi_{t+1} (\pi_{t+1} - 1). \tag{3.3}$$

Absent relative price distortions, the average wage is

$$w_t = C_t \left( \frac{Y_t}{A_t} \right)^{\phi v}. \tag{3.4}$$

The costs of price adjustment affect consumers by reducing profit share. Consequently, the household budget constraint implies the market clearing condition

$$C_t = Y_t - \frac{\xi}{2} (\pi_t - 1)^2. \tag{3.5}$$

# 4. Optimal steady state

## 4.1. Ramsey problem

To approximate the model one chooses an appropriate point for the approximation. The first step is to formulate a Ramsey problem. Hence,

$$\max E_0 \sum_{t=0}^{\infty} \beta^t \left( \log(C_t) - \frac{\lambda}{1+v} \left( A_t^{-1} Y_t \right)^{\phi(v+1)} \right), \tag{4.1}$$

subject to market clearing (3.5) and pricing behavior (4.2)

$$(\theta - 1) Y_t - \theta \phi \mu_t \lambda C_t \left( A_t^{-1} Y_t \right)^{\phi(v+1)} + \xi \pi_t (\pi_t - 1) = E_t \beta \frac{C_t}{C_{t+1}} \xi \pi_{t+1} (\pi_{t+1} - 1). \tag{4.2}$$

Next, one solves this problem assuming commitment; we adopt the "timeless perspective" of Benigno and Woodford (2005). Thus, optimal policy under commitment implies zero inflation. From (3.5) one finds

$$C = Y \tag{4.3}$$

and, using (3.3) and (3.4), that the optimal level of steady state output is

$$\mu\lambda Y^{\phi(v+1)} = \frac{\theta - 1}{\theta\phi}. \tag{4.4}$$

## 5. Second-order approximation

One now constructs the second-order approximation to social welfare which coincides with the objectives of the representative individual. Thus,

$$\begin{aligned} U &= E_0 \sum_{t=0}^{\infty} \beta^t \left[ \log(C_t) - \frac{\lambda}{1+v} \left( A_t^{-1} Y_t \right)^{\phi(v+1)} \right] \\ &= E_0 \sum_{t=0}^{\infty} \beta^t \left[ \widehat{C}_t - \frac{\theta - 1}{\theta\mu} \left( \widehat{Y}_t - \widehat{A}_t \right) - \frac{1}{2} \frac{(\theta - 1)(1+v)\phi}{\theta\mu} \left( \widehat{Y}_t - \widehat{A}_t \right)^2 \right] + O_3. \end{aligned} \tag{5.1}$$

$O_3$ indicates terms of third and higher order. The second-order approximation to market clearing, (3.5), is

$$\widehat{Y}_t = \widehat{C}_t + \frac{\xi}{2Y} \widehat{\pi}_t^2 + O_3. \tag{5.2}$$

Combining (5.1) and (5.2) one obtains

$$\begin{aligned} U &= \Phi E_0 \sum_{t=0}^{\infty} \beta^t \left( \widehat{Y}_t - \widehat{A}_t \right) \\ &\quad - \frac{\xi}{2Y} \sum_{t=0}^{\infty} \beta^t \widehat{\pi}_t^2 - \frac{1}{2} (1 - \Phi)(1+v)\phi \sum_{t=0}^{\infty} \beta^T \left( \widehat{Y}_t - \widehat{A}_t \right)^2 + O_3 + tip, \end{aligned} \tag{5.3}$$

where $\Phi := 1 - \frac{\theta-1}{\theta}\frac{1}{\mu}$ is a constant which sums up all the distortions in the economy[3]. Finally, one derives a second-order approximation to price setting

[3] *tip* denotes terms independent of policy. Broadly speaking, it collects terms that are not functions of policy. See Woodford (2003).

behavior (equation (6.1) in the appendix). That delivers an expression for the second-order approximation to social welfare in terms of output and inflation:

$$\begin{aligned} U &= -\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left(\widehat{Y}_t-\widehat{A}_t+\frac{\Phi}{\phi(v+1)}\widehat{\mu}_t\right)^2 \\ &\quad -\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\frac{\xi}{(1+v)\,\phi Y}\widehat{\pi}_t^2\left[\frac{\Phi}{(1+v)\,\phi}+1\right]+O_3+tip. \end{aligned} \tag{5.4}$$

Note, the Phillips curve (derived in the appendix) takes the same form in both the Calvo and Rotemberg specifications; all that differs is the $\kappa$ parameter[4]:

$$\kappa_i^{-1}\left(\widehat{Y}_t-\widehat{A}_t\right)=\widehat{\pi}_t-\beta E_t\widehat{\pi}_{t+1}+\widetilde{\mu}_t+O_2,\quad i=R,C \tag{5.5}$$

where $\kappa_R=\frac{\xi}{(\theta-1)Y}\phi(v+1)$ denotes the slope of the Rotemberg Phillips Curve[5] and where $\kappa_C=\frac{(1-\beta\alpha)(1-\alpha)}{\alpha}\frac{\phi(1+v)}{(\theta\phi(1+v)-\theta+1)}$ is the slope of the Calvo Phillips Curve. The Rotemberg social objective (5.4) is

$$U_R=-\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t y_t^2-\frac{1}{2}\kappa_R\left[\frac{\Phi}{(1+v)\,\phi}+1\right](\theta-1)\,E_0\sum_{t=0}^{\infty}\beta^t\widehat{\pi}_t^2+O_3+tip, \tag{5.6}$$

where $y_t := \left(\widehat{Y}_t-\widehat{A}_t+\frac{\Phi}{\phi(v+1)}\widehat{\mu}_t\right)$. Now one can compare this with the Calvo version[6]:

$$U_C=-\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t y_t^2-\frac{1}{2}\theta\kappa_C E_0\sum_{t=0}^{\infty}\beta^t\widehat{\pi}_t^2+O_3+tip.$$

The Rotemberg model delivers a very similar objective function to the Calvo model. First, optimal policy tries to minimize inflation and output gaps. Furthermore, and more surprisingly, the coefficient on the inflation term in $U_R$ is close to $(1/2)\theta\kappa_C$, assuming, via normalization of $\xi$, that the slopes of the Phillips curves are identical. Indeed, for a realistic parameterization, the ratio of the weights on inflation across loss functions is equal to unity plus or minus 20%,

[4] See equation (30) in Benigno and Woodford (2005).

[5] For convenience, $\widetilde{\mu}_t := \frac{\widehat{\mu}_t}{(1+v)\phi}$

[6] $U_C$ corresponds to equation (32) in Benigno and Woodford (2005). Our formulation is simpler because we have fewer sources of uncertainty; we only include productivity and cost-push shocks.

approximately. However, observe that in the Rotemberg social welfare function the weight on inflation increases in the inefficiency of the economy; the larger the distortions, the larger the cost of inflation fluctuations. In contrast, in the Calvo set-up it is only the degree of competition, $\theta$, that affects the inflation weight[7]. Why? In the Rotemberg model there is a wedge between output and consumption that is proportional to the square of inflation, see (3.5). However, in the Calvo model that wedge is absent and the principle distortions are included in the Phillips curve. Finally, by setting $\Phi = 0$ one can compare objectives in the non-distorted steady state case. Again, assuming $\kappa_C = \kappa_R$, the inflation weights differ only marginally; $(1/2)\theta\kappa_C$ compared with $(1/2)(\theta - 1)\kappa_R$[8].

### 5.1. Concluding remarks

The Rotemberg approximate social welfare function is very similar to the Calvo model's if linearized around a zero inflation steady state both in terms of functional form and coefficients. However, the degree of distortion in the economy influences inflation aversion in Rotemberg's framework in a way that has no counterpart in Calvo's setup. Finally, we emphasize that these two model economies behave very differently under trend inflation (see Damjanovic and Nolan (2008)).

[7] Had we used CRRA utility, $\Phi$ would have appeared in $U_C$ also.

[8] $\theta$ usually takes values between 7 and 10 in applied work.

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# 6. Appendix: derivation of (5.4)

The price setting relation (4.2) is approximated as

$$\widehat{Y}_t - \widehat{T}_t + \frac{\xi}{(\theta-1)\,Y}\widehat{\pi}_t - \frac{\beta\xi}{(\theta-1)\,Y}E_t\widehat{\pi}_{t+1} + \tag{6.1}$$
$$\frac{1}{2}\left(\widehat{Y}_t^2 - \widehat{T}_t^2\right) + \frac{3}{2\,(\theta-1)\,Y}\xi\left(\widehat{\pi}_t^2 - \beta\widehat{\pi}_{t+1}^2\right) - \frac{\beta\xi}{(\theta-1)\,Y}\left(\widehat{C}_t - \widehat{C}_{t+1}\right)\widehat{\pi}_{t+1} = O_3.$$

Here $T_t$ stands for total production costs satisfying the identity

$$\widehat{T}_t = \widehat{\mu}_t + \widehat{C}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right). \tag{6.2}$$

Hence, the first order approximation to (4.2) is familiar

$$\frac{\xi}{(\theta-1)\,Y}\left(\widehat{\pi}_t - \beta E_t\widehat{\pi}_{t+1}\right) = \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right) + \widehat{\mu}_t + O_2 \tag{6.3}$$

One may integrate forward (6.1) yielding

$$E_0\sum_{t=0}^{\infty}\beta^t\left(\widehat{Y}_t - \widehat{T}_t\right) + \frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left(\widehat{Y}_t^2 - \widehat{T}_t^2\right) =$$
$$\frac{\beta\xi}{(\theta-1)\,Y}E_0\sum_{t=0}^{\infty}\beta^t\left(\widehat{C}_t - \widehat{C}_{t+1}\right)\widehat{\pi}_{t+1} + tip + O_3.$$

Combining this with (5.2) and (6.2) obtains

$$E_0\sum_{t=0}^{\infty}\beta^t\phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right) + tip + O_3 =$$
$$-\,E_0\sum_{t=0}^{\infty}\beta^t\frac{\xi}{2Y}\widehat{\pi}_t^2 - \frac{\beta\xi}{(\theta-1)\,Y}E_0\sum_{t=0}^{\infty}\beta^t\left(\widehat{Y}_t - \widehat{Y}_{t+1}\right)\widehat{\pi}_{t+1}$$
$$-\,\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]\left[2\widehat{Y}_t + \widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right].$$

$$(6.4)$$

Now, multiplying both sides of (6.3) by $\widehat{Y}_t$, yields

$$\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]\widehat{Y}_t = \frac{\xi}{(\theta-1)\,Y}\left(\widehat{\pi}_t\widehat{Y}_t - \beta E_t\widehat{\pi}_{t+1}\widehat{Y}_t\right) + O_3,$$

which solved forward gives

$$\sum_{t=0}^{\infty}\beta^t\left[\frac{\xi}{(\theta-1)\,Y}\widehat{\pi}_t - \left(\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right)\right]\widehat{Y}_t =$$
$$\frac{\beta\xi}{(\theta-1)\,Y}\sum_{t=0}^{\infty}\beta^t E_t\widehat{\pi}_{t+1}\widehat{Y}_t + tip + O_3.$$

That expression, in turn, is rewritten as

$$\frac{\beta\xi}{(\theta-1)\,Y}\sum_{t=0}^{\infty}\beta^t E_t\widehat{\pi}_{t+1}\left(\widehat{Y}_t - \widehat{Y}_{t+1}\right) = \tag{6.5}$$
$$-\sum_{t=0}^{\infty}\beta^t\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]\widehat{Y}_t + tip + O_3.$$

Combining (6.5) with (6.4) results in

$$\sum_{t=0}^{\infty}\beta^t\phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right) =$$
$$-\sum_{t=0}^{\infty}\beta^t\frac{\xi}{2Y}\widehat{\pi}_t^2 - \sum_{t=0}^{\infty}\beta^t\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]\widehat{Y}_t$$
$$-\frac{1}{2}\sum_{t=0}^{\infty}\beta^t\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]\left[2\widehat{Y}_t + \widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right] + tip + O_3,$$

which can be simplified as

$$\sum_{t=0}^{\infty}\beta^t\phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right) = -\sum_{t=0}^{\infty}\beta^t\frac{\xi}{2Y}\widehat{\pi}_t^2 - \frac{1}{2}\sum_{t=0}^{\infty}\beta^t\left[\widehat{\mu}_t + \phi(v+1)\left(\widehat{Y}_t - \widehat{A}_t\right)\right]^2 + tip + O_3. \tag{6.7}$$

The expression for welfare reported as expression (5.6) is obtained by combining (6.7) with (5.3).

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