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RELATIVE PRICE DISTORTION AND OPTIMAL MONETARY POLICY IN OPEN ECONOMIES

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This paper provides a closed-form solution for optimal monetary policy in a two-country model with Calvo-type sticky prices. Initial price dispersion makes it suboptimal to completely stabilize the producer price index, and the optimal policy would entail a price-level targeting. The solution also indicates that the isomorphism of optimal policy rules between closed and open economy breaks down unless the utility function is logarithmic in consumption.

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I. INTRODUCTION

Much of the recent literature in open macroeconomics has addressed the issue of how to conduct monetary policy in open economy models that include imperfect competition and nominal rigidities as mechanisms for non-neutralities of monetary policies. Many of the recent new models have been used to analyze the desirability of full price stability and the character of international policy interdependence in open economies. In

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particular, Benigno and Benigno (2004) and Clarida, Gali, and Gertler (2002) analyzed the cases for price stability as a characteristic of optimal monetary policy and showed an isomorphism of optimal policy between closed and open economies.[1]

In this paper, we consider an optimal policy problem in a two-country model with Calvo-type sticky prices. Our model inherits a simple structure that inherits from much of the recent open-economy literature, such as unit elasticity of substitution between domestic and foreign goods and price setting in terms of producers' currencies. The key difference from the existing literature is that we explicitly allow for dynamic movements of relative price distortion responding to inflation and initial price dispersion, as done in a closed-economy setting by Yun (2005).

We assume that governments seek to maximize the welfare of their own households among feasible allocations derived under the restriction that the optimal allocation can be implemented in a decentralized economy. This paper provides a closed-form solution for this problem in the presence of initial price dispersion, and shows that the second-best equilibrium is *not* to maintain full price stability even though full price stability is still available. It has also been remarked in the recent literature on international monetary policy that the similarity of optimal monetary policy rules between closed and open economies is a robust result in a non-cooperative setting. However, this paper shows that variations in relative price distortion help to generate international links in terms of output gap and break down the isomorphism result.

II. MODEL

This section presents a two-country open economy version of the sticky price model with Calvo-type pricing. Our model closely follows that of Clarida, Gali, and Gertler (2002), but excludes their exogenous wage markup shock.[2] This exclusion is to focus on our main contribution of deriving the dynamics of relative price distortion and analyzing its effect

[1] Two additional papers of particular relevance are Gali and Monacelli (2005) in a small open economy, and Clarida, Gali, and Gertler (2001) in a linear-quadratic framework.
[2] Also using a similar structure are Clarida, Gali, and Gertler (2001), Benigno and Benigno (2004), and Gali and Monacelli (2005).

on the aggregate supply curve in open economies.

2.1 Households

The behavior of households is standard. The preference at period 0 of the representative household in the home country is summarized by

$$\sum_{t=0}^{\infty} \beta^t E_0[U(C_t) - V(N_t)], \tag{2.1}$$

where β is the time discount factor, and N_t and C_t denote the hours worked, a composite consumption index in per-capita terms. The utility function $U(C_t)$ is concave in C_t, while $V(N_t)$ is convex in N_t. The composite consumption index is a Cobb-Douglas function of the form:

$$C_t = C_{H,t}^{1-\gamma} \, C_{F,t}^{\gamma},$$

where $0 < \gamma < 1$, and $C_{H,t}$. and $C_{F,t}$ are domestic and foreign consumption goods, respectively. The corresponding consumer price index is then given by

$$P_t = \kappa^{-1} C_{H,t}^{1-\gamma} \, P_{F,t}^{\gamma}, \tag{2.2}$$

where $\kappa = (1-\gamma)^{1-\gamma} \gamma^{\gamma}$.

There are two countries, home and foreign, which differ in population size. The home country has a population share of $(1-\gamma)$ and the share of the foreign country is γ. In addition, the consumption and consumer price indices for the foreign country are symmetrically defined as $C_t^* = C_{H,t}^{*\ 1-\gamma} C_{F,t}^{*\ \gamma}$ and $P_t^* = \kappa^{-1} P_{H,t}^{*\ 1-\gamma} P_{F,t}^{*\ \gamma}$, where '*' is used to represent quantities and prices in the foreign country.

The representative household maximizes (2.1) subject to $C_t + E_t[Q_{t,t+1} B_{t+1} / P_{t+1}] = B_t / P_t + (1-\tau) W_t N_t / P_t - T_t$ in each period, where $Q_{t,t+1}$ is the stochastic discount factor used for computing the value at period t of a unit of consumption goods at period $t+1$, B_{t+1} is the nominal payoff at period $t+1$ of the portfolio held at period t, T_t is the real lump-sum tax, W_t is the nominal wage at period *t*, and τ is the subsidy rate at period *t* for labor supply. In particular, following the literature, the magnitude of the subsidy rate in each period will be determined endogenously to eliminate distortions associated with imperfect competition and openness in goods market, while the subsidy is funded by the lump-sum tax imposed on households.

It is assumed that households in the home and foreign countries have the same preferences over consumption and labor as that described in (2.1). Under a suitable normalization of initial conditions, the assumption of complete markets—though a simple asset market with only bonds would suffice—makes domestic consumption equal to foreign consumption: $C_t = C_t^*$.

2.2 Technology

There are two types of domestic goods: intermediate goods and final goods. Domestic intermediate goods are sold only to domestic firms producing final goods, while domestic final goods can be purchased by both domestic and foreign households. In addition, the markets for final goods are perfectly competitive and the number of final goods producers in each country equals its population size. Moreover, each intermediate goods firm *z* produces type *z* of intermediate goods indexed in a unit interval [0, 1] and sets its price as a monopolistic competitor.

Let Y_t denote the output level at period *t* of a final goods producer. In addition, all domestic final goods are produced using the same technology: $Y_t = (\int_0^1 Y_t(z)^{\frac{\varepsilon-1}{\varepsilon}} dz)^{\frac{\varepsilon}{\varepsilon-1}}$, where $\varepsilon > 1$ and $Y_t(z)$ denotes the demand of a final goods producer for an intermediate goods *z*.

Each final goods producer minimizes its cost of producing Y_t, taking intermediate goods prices as given. The demand curve of each intermediate goods *z* is then given by $Y_t(z) = (P_{H,t}(z)/P_{H,t})^{-\varepsilon} Y_t$, where $Y_t(z)$ is the demand at period *t* for intermediate goods produced by firm *z*, $P_{H,t}(z)$ denotes the price at period *t* of the intermediate goods *z*, and $P_{H,t}$ denotes the price index of the domestic intermediate goods. In addition, the price index for domestic intermediate goods is defined by

$$P_{H,t} = (\int_0^1 P_{H,t}(z)^{1-\varepsilon} dz)^{\frac{1}{1-\varepsilon}} . \tag{2.3}$$

Having described the behavior of final goods firms, the analysis turns to the price setting of intermediate goods firms. Each firm *z* employs labor to produce its product *z* using a linear production function:

$$Y_t(z) = A_t N_t(z) , \tag{2.4}$$

where $N_t(z)$ is the number of hours hired by firm *z* and $Y_t(z)$ denotes the output level of the domestic firm *z*. In addition, the labor market is assumed to be perfectly competitive and nominal wage is completely flexible. It thus implies that the nominal marginal cost of producing intermediate goods is the same across firms: $MC_t = W_t / A_t$, where MC_t denotes the nominal marginal cost at period *t*.

2.3 Sticky prices and relative price distortion

Following Calvo (1983) and Yun (2005), a fraction of intermediate goods producers, $1-\alpha$, are allowed to choose a new optimal price at period *t*, $P^*_{H,t}$, in each period $t = 0, 1, \ldots, \infty$. In addition, the other fraction of firms do not change their previous prices. Hence, the Calvo-type staggering allows one to rewrite the price index definition equation (2.3) as follows:

$$1 = (1-\alpha)(\frac{P^*_{H,t}}{P_{H,t}})^{1-\varepsilon} + \alpha \Pi^{\varepsilon-1}_{H,t} , \tag{2.5}$$

where $\Pi_{H,t} = P_{H,t} / P_{H,t-1}$ denotes the ratio of a domestic producer's price level at period *t* to its level at period $t-1$.

Next, the analysis turns to the discussion of the relationship between inflation rate and relative price distortion. It also follows from (2.4) that, if individual outputs are linearly aggregated, the aggregate production function can be written as

$$Y_t = \frac{A_t}{\Delta_t} N_t , \tag{2.6}$$

where $N_t = \int_0^1 N_t(z)dz$. In particular, Δ_t denotes a measure of the relative price distortion for the price index of domestic goods:

$$\Delta_t = \int_0^1 (\frac{P_{H,t}(z)}{P_{H,t}})^{-\varepsilon} dz .$$

In order to obtain the relationship between inflation rate and relative price distortion, under the Calvo-type staggered price-setting, we rewrite our measure of relative price distortion specified above as follows:

$$\Delta_t = (1-\alpha)(\frac{P^*_{H,t}}{P_{H,t}})^{-\varepsilon} + \alpha\Pi^{\varepsilon}_{H,t}\Delta_{t-1}. \tag{2.7}$$

Hence, substituting (2.5) into (2.7), one can derive a law of motion for relative price distortions:

$$\Delta_t = (1-\alpha)(\frac{1-\alpha\Pi^{\varepsilon-1}_{H,t}}{1-\alpha})^{\frac{\varepsilon}{\varepsilon-1}} + \alpha\Pi^{\varepsilon}_{H,t}\Delta_{t-1}. \tag{2.8}$$

As a result, one can see from equation (2.8) that the current level of relative price distortion depends on the current rate of the producer price index inflation and the previous level of relative price distortion.[3]

2.4 Profit maximization and Phillips curve

In addition, the profit-maximization problem under the Calvo-type staggered pricesetting can be written as

[3] See Woodford (2003) for a detailed discussion on how one can derive a quadratic loss function from the utility function of the household, in which a measure of price dispersion in the Calvo model is defined as a cross-section variance of logarithms of individual prices. Additionally, see Schmitt-Grohé and Uribe (2004) for an explicit discussion on how to derive a measure of relative price distortion in the Calvo model, which is identical to the one used here.

$$\max_{P^*_{H,t}} \sum_{k=0}^{\infty} \alpha^k E_t[Q_{t,t+k}(\frac{P_{H,t+k}}{P_{t+k}}\frac{P^*_{H,t}}{P_{H,t+k}} - mc_{t+k})(\frac{P^*_{H,t}}{P_{H,t+k}})^{-\varepsilon} Y_{t+k}]$$

where $mc_t = MC_t / P_t$, $Q_{t,t+k}$ denotes the stochastic discount factor used to compute the value at period t of one unit of consumption goods at period $t+k$ for $k = 1, 2, \ldots, \infty$ and $Q_{t,t}$. The first-order condition for $P^*_{H,t}$ can be written as

$$\frac{P^*_{H,t}}{P_{H,t}} = \frac{I_t}{K_t}, \tag{2.9}$$

where I_t and K_t are defined as
$I_t = \sum_{k=0}^{\infty} (\alpha\beta)^k E_t[U'(C_{t+k})(P_{H,t} / P_{H,t+k})^{-\varepsilon}(\varepsilon / (\varepsilon - 1))mc_{t+k}Y_{t+k}]$ and
$K_t = \sum_{k=0}^{\infty} (\alpha\beta)^k E_t[U'(C_{t+k})(P_{H,t+k} / P_{t+k})(P_{H,t} / P_{H,t+k})^{1-\varepsilon} Y_{t+k}]$.

2.5 Resource constraint and trade balance

We close the description of the model by considering equilibrium conditions to obtain a relationship between the aggregate consumption and production factor input. As noted earlier, the number of final goods producers equals the size of the population in each of the two countries. The aggregate market clearing for domestic and foreign goods, therefore, can be written as $(1-\gamma)Y_t = (1-\gamma)C_{H,t} + \gamma C^*_{H,t}$ and $\gamma Y^*_t = (1-\gamma)C_{F,t} + \gamma C^*_{F,t}$. It is well known that, in our setup of unit elasticity of substitution between home and foreign goods, the trade balance is 0:

$$P_{H,t}Y_t = P_t C_t, \tag{2.10}$$
$$P^*_{F,t}Y^*_t = P^*_t C^*_t. \tag{2.11}$$

Let S_t denote the terms of trade at period t of the home country, which is defined as the ratio of the price index of imported goods to that of exported goods, i.e. $S_t = P_{F,t} / P_{H,t}$. Then, dividing both sides of (2.11) by their corresponding sides of (2.10) and applying the law of one price to the resulting equation, one can obtain an expression of the terms of trade in terms of the ratio of the output level of the home country to that of the foreign country:

$$S_t = \frac{Y_t}{Y_t^*}. \tag{2.12}$$

In addition, the consumption price index (2.2) leads to $P_t / P_{H,t} = \kappa^{-1} S_t^{\gamma}$, while equation (2.10) implies $P_t / P_{H,t} = Y_t / C_t$. Then, combining these two equations' results in $C_t = \kappa\, Y_t S_t^{-\gamma}$. Hence, substituting (2.12) into this equation, one can show that per capita consumption in the home country is a Cobb-Douglas function of domestic and foreign final goods of the form:

$$C_t = \kappa Y_t^{1-\gamma} Y_t^{*\gamma}. \tag{2.13}$$

III. OPTIMAL MONETARY POLICY

This section analyzes an optimal policy problem of the government that maximizes the expected utility of the representative household, while taking as a given the foreign economic activity as well as the initial price dispersion within the home country.[4]

3.1 Optimal policy problem and closed-form solution

Our optimal policy problem is subject to two implementation constraints as well as social resource constraint. However, this dynamic problem can be reduced to a simple univariate static problem as follows. We first argue that the solution to the problem without the two implementation constraints satisfies the two constraints, which implies that these two constraints can be ignored. The Social resource constraint is then broken into two parts, and our optimal policy problem is also broken into two problems, each problem with a single constraint.

[4] We discuss how to implement this second-best allocation in a decentralized economy in the Appendix.

One implementation constraint comes from the present-value budget constraint of the representative household. However, in our setting with lump-sum taxes, this implementation constraint is not binding, and so it can be ignored in our optimal policy problem.[5] The other implementation constraint is the profit maximization condition (2.9). When firms are allowed to set prices, they take into account what will take place during future periods. However, it can be shown that the optimal pricing equation is satisfied with the solution to a planning problem that ignores it.[6] The optimal pricing equation, (2.9), is therefore simply ignored at this point.

In addition to the implementation constraints, the optimal policy is also subject to two equations describing social resource constraint. One of them comes from combining the consumption behavior (2.13) and the aggregate production function (2.6):

$$C_t = \kappa Y_t^{*\gamma} \left(\frac{A_t}{\Delta_t} N_t\right)^{1-\gamma}. \tag{3.1}$$

Since this equation depends on the relative price distortion, the law of motion for relative price distortion (2.8) should be added as a constraint. The optimal policy problem itself can also be broken into two recursive parts. One part is to maximize the period utility subject to (3.1) for given values of Y_t^* and Δ_t. The other part is the choice of $\Pi_{H,t}$ to minimize Δ_t as defined in (2.8) for given values of Δ_{t-1}. This last problem is a simple univariate static problem, the solution to which is

$$\Pi_{H,t} = (\alpha + (1-\alpha)\Delta_{t-1}^{\varepsilon-1})^{\frac{-1}{\varepsilon-1}}.$$

Under the optimal policy, the resulting dynamics for the relative price distortion is

[5] This constraint cannot be ignored if only distorting taxes are available, as illustrated in Benigno and Woodford (2006). Also see Chari and Kehoe (1999) for a survey of optimal policies in real and monetary economies with distorting taxes and full price flexibility.

[6] This is due to the appropriately chosen subsidy rate and the constant-returns-to-scale production function. See the Appendix on decentralization for the proof.

$$\Delta_t = \Delta_{t-1}(\alpha + (1-\alpha)\Delta_{t-1}^{\varepsilon-1})^{\frac{-1}{\varepsilon-1}}. \tag{3.2}$$

and the choice of domestic producer price inflation can also be expressed as

$$\Pi_{H,t} = \frac{\Delta_t}{\Delta_{t-1}}. \tag{3.3}$$

It is clear from (3.2) that the absence of the initial price dispersion leads to $\Delta_t = 1$ for $t = 1, 2, \ldots, \infty$, 1. It then follows from (3.3) that the optimal monetary policy stabilizes the price level completely if the initial price dispersion does not exist. However, if the initial price dispersion does exist, the optimal monetary policy allows for a gradual transition of the relative price distortion toward the steady state with no price dispersion.

Furthermore, it can be shown that while the optimal policy leads to zero steady state inflation, it may lead the producer price index to converge to a new steady state level. The new steady state level may differ from its initial level in the period before the central bank begins its optimal policy. In order to see this, one can use Equation (3.2) to show that the optimal level at period *t* of the producer price index can be written as

$$P_{H,t} = \frac{P_{H,-1}}{\Delta_{-1}}\Delta_t. \tag{3.4}$$

where $P_{H,-1}$ and Δ_{-1} denote the producer price level and relative price distortion in the period before the monetary authority begins the optimal policy, respectively. It also follows from (3.2) that $\lim_{t\to\infty}\Delta_t = 1$. The steady state level of the producer price index is therefore given by $P_H^{\circ} = P_{H,-1}/\Delta_{-1}$, when P_H° denotes the steady state level of the producer price index. Thus, the steady state price level under the optimal policy equals the initial price level deflated by the initial level of relative price distortion.

On the other hand, the steady state level of the producer price index discussed above can be interpreted as the optimal target that is implied by the optimal policy. In particular, taking the logarithm to both sides of (3.4), it can be shown that the optimal policy makes the logarithm of relative price distortion equal the log level of the producer price index from its target:

$$\delta_t = p_{H,t} - p_H^{\circ}, \tag{3.5}$$

where $\delta_t = \log \Delta_t$; $p_{H,t} = \log P_{H,t}$, and $p_H^{\circ} = \log P_H^{\circ}$. As a result, one can conclude that initial price dispersion makes it optimal for the central bank to pursue price-level targeting in terms of producer price index. However, it is optimal to achieve zero inflation in terms of the producer price index if the initial price dispersion does not exist.

3.2 Functional form and (non-)isomorphism

To discuss our optimal monetary policy in the context of isomorphism between closed and open economies, we adopt a popular functional form for the utility function. As in Clarida, Gali, and Gertler (2002), the instantaneous utility functions for consumption and labor are assumed to take the following functional forms:

$$U(C_t) = \frac{C_t^{1-\sigma} - 1}{1-\sigma}; \;\; V(N_t) = \frac{N_t^{1+\nu}}{1+\nu}, \tag{3.6}$$

where $\sigma > 0$ and $\nu \geq 0$.

Given that households in the two countries have the same utility function as that specified in (3.6), home and foreign consumption-leisure trade-off conditions are as follows.

$$(1-\gamma)C_t^{1-\sigma} = N_t^{1+\nu}. \tag{3.7}$$

$$\gamma C_t^{*1-\sigma} = N_t^{*1+\nu}. \tag{3.8}$$

Substituting these two equations into (3.1), with the aggregate production function of the foreign country, and setting $C_t = C_t^*$ in the resulting equation, one can show that the optimal level of consumption in the non-cooperative case becomes

$$C_t = C_t^* = \kappa^{\frac{2+\varphi}{\sigma+\nu}}((\frac{A_t}{\Delta_t})^{1-\gamma}(\frac{A_t^*}{\Delta_t^*})^{\gamma})^{\frac{1+\nu}{\sigma+\nu}}. \tag{3.9}$$

Additionally, plugging (3.9) into (3.7) and (3.8), respectively, the optimal numbers of the per capita hours worked at period t in the two countries are given by

$$N_t = \kappa_n((\frac{A_t}{\Delta_t})^{1-\gamma}(\frac{A_t^*}{\Delta_t^*})^{\gamma})^{\frac{1+\sigma}{\sigma+\nu}}; \;\; N_t^* = \frac{\kappa_n^*}{\kappa_n}N_t, \tag{3.10}$$

where parameters κ_n and κ_n^* are defined as

$$\kappa_n = (1-\gamma)^{\frac{1}{1+\nu}}\kappa^{\frac{(2+\nu)(1-\sigma)}{(\sigma+\nu)(1+\nu)}}; \;\; \kappa_n^* = \gamma^{\frac{1}{1+\nu}}\kappa^{\frac{(2+\nu)(1-\sigma)}{(\sigma+\nu)(1+\nu)}}.$$

Having obtained equilibrium levels of consumption and labor, it is now possible to compute the equilibrium level of output. In order to obtain the simplicity of the analysis, it is useful to denote the elasticity of the domestic hours with respect to the domestic aggregate productivity by η_1 and the elasticity of the hours with respect to the foreign aggregate productivity by η_2. It then follows from (3.10) that the two elasticities are, respectively, given by

$$\eta_1 = 1(1-\gamma)b; \;\; \eta_2 = -\gamma b; \;\; b = \frac{\sigma-1}{\sigma+\nu}. \tag{3.11}$$

It is clear from (3.11) that b is positive if $\sigma > 1$, and that it is negative if $\sigma < 1$. Using the two elasticities specified in (3.11), the substitution of (3.10) into the aggregate production functions, home and abroad, leads to the equilibrium levels of output as follows:

$$Y_t = \kappa_n (\frac{A_t}{\Delta_t})^{1+\eta_1} (\frac{A_t^*}{\Delta_t^*})^{\eta_2}\ ;\ \ Y_t^* = \kappa_n^* (\frac{A_t}{\Delta_t})^{\eta_1} (\frac{A_t^*}{\Delta_t^*})^{1+\eta_2}\ . \tag{3.12}$$

Before proceeding to the discussion of isomorphism of optimal monetary policy between closed and open economies, it may be worthwhile to consider two special cases of the equilibrium levels of output described in (3.12). First, if relative price distortion does not exist at home or abroad, the efficient level of output is determined only by the aggregate technology levels in the two countries. Second, the effect of a change in foreign relative price distortion on the domestic output depends on the value of η_2. Specifically, since $\sigma = 1$ leads to $\eta_2 = 0$, the domestic output is not affected by changes in foreign economic activities when intertemporal substitution has a unit elasticity.[7]

We will see shortly that the isomorphism holds in these two special cases. Many papers—including Clarida, Gali, and Gertler (2002) and Benigno and Benigno (2003)—have also extended this isomorphism result into a general non-unit-elasticity case in the presence of initial price distortion. However, we show that this generalization is not an accurate statement in this section, and in the next section will illustrate this difference in the framework of a linear-quadratic approximation.

The natural level of output in the non-cooperative case is defined as the equilibrium level of output that would be obtained if both home and foreign countries achieved the first-best allocations. Having defined the natural level of output, one can use (3.12) to show that the natural levels of output for the two countries in the non-cooperative case can be written as follows:

$$\overline{Y}_t = \kappa_n A_t^{1+\eta_1} A_t^{*\eta_2}\ ;\ \ \overline{Y}_t^* = \kappa_n^* A_t^{\eta_1} A_t^{*1+\eta_2}\ , \tag{3.13}$$

where $\overline{Y}_t$ denotes the natural level of output for the home country and $\overline{Y}_t^*$ denotes the natural level of output for the foreign country. Notice

[7] Corsetti and Pesenti (2002) have analyzed the relationship between the size of intertemporal substitution and the effect of foreign monetary shocks on domestic output. Clarida, Gali, and Gertler (2002) have discussed how a change in the size of intertemporal substitution can alter the relationship between foreign output and domestic real marginal cost.

that the natural levels of output described in (3.13) are independent of monetary policies in the home and foreign countries.

The output gap in equilibrium is defined as the log-difference of the equilibrium level of output from its natural level. Let x_t denote the output gap at period *t* in the home country. Then, taking logarithm to both sides of (3.12) and (3.13) and combining the resulting equations, one can obtain an expression of the optimal output gap under the non-cooperative case in terms of the measures of domestic and foreign relative price distortions:

$$x_t = -(1+\eta_1)\delta_t - \eta_2\delta_t^* . \tag{3.14}$$

Similarly, the output gap in the foreign country can be written as

$$x_t^* = -\eta_1\delta_t - (1+\eta_2)\delta_t^* , \tag{3.15}$$

where x_t^* denotes the output gap at period *t* in the foreign country. As a result, substituting (3.5) and its foreign analog into (3.14) and (3.15), one can obtain the following optimal relationship between output gap and producer price index:

$$x_t = -(1+\eta_1)(p_{H,t} - p_H^{\circ}) - \eta_2(p_{F,t}^* - p_F^{*\circ}) , \tag{3.16}$$

$$x_t^* = -\eta_1(p_{H,t} - p_H^{\circ}) - (1+\eta_2)(p_{F,t}^* - p_F^{*\circ}). \tag{3.17}$$

The policy implications that follow from equations (3.16) and (3.17) can be summarized in this way. These two equations imply that the optimal policy has central banks adjust output gap in response to the deviations of domestic and foreign producer price indices from their targets. However, the size of intertemporal substitution determines the sign of the output effect of a deviation of the foreign producer price index from its target, which has been emphasized in recent literature.[8] Specifically, note that $\eta_2 = 0$ if $\sigma = 1$, while $\eta_2 > 0$ if $\sigma < 1$, and

[8] See, for example, Corsetti and Pesenti (2001a), G. Benigno and P. Benigno (2002), and Clarida, Gali, and Gertler (2002). Refer to Lane (2001) for a detailed discussion of international policy interdependence in open economies.

$\eta_2 < 0$ if $\sigma > 1$. As a result, given that the relationship between the two parameters holds, the presence of the initial price dispersion in the two countries leads to the break-down of the isomorphism result—as in Clarida, Gali, and Gertler (2002)—of the optimal policy rules between closed and open economies, unless $\sigma = 1$. Moreover, it is optimal to contract the aggregate demand in response to a rise in the foreign producer price index from its target if $\sigma < 1$, while it is optimal to stimulate the aggregate demand if $\sigma > 1$.

IV. CONCLUSION

This paper has analyzed the second-best equilibrium in an open-economy model with nominal price rigidity and showed that staggered price-setting can generate an independent channel for international interdependence of monetary policy. In particular, the isomorphism of optimal monetary policy between closed and open economies can break down in the presence of initial price dispersion.

It is worth discussing special assumptions on the role of fiscal policy and fiat money as well as preferences of households, which are crucial for obtaining an analytical solution to the optimal policy problem without approximation. Specifically, this paper has assumed that fiscal policy is used to eliminate the distortions associated with imperfect competition and openness in the goods market, and that money only plays the role of unit account, following much of the recent literature on monetary policy. Furthermore, this paper has assumed unitary elasticity of substitution between domestic and foreign goods, complete exchange rate pass-through, and a complete financial market. Given that these features hold, the paper finds that the optimal monetary policy in an open economy with nominal price rigidity of Calvo pricing produces an analytical solution without having to rely on any approximation, which is time-consistent.

Thus, the set of special assumptions can be interpreted as a set of sufficient conditions to obtain a closed-form solution to the optimal monetary policy in an open economy with Calvo-type staggered price-setting. An implication of such results for future research is to relax these special assumptions and analyze its consequences on the optimal policy, taking into account the role of relative price distortion in making monetary policy interdependent across countries. Kim, Levin, and Yun (2005) discuss the importance of relative price distortion and its relationship to the approximation methods used in the literature.[9]

[9] From the perspective of linear quadratic approximation as adopted in Clarida, Gali, and Gertler (2002), our setup is different from theirs in the following two ways. First, the objective function should include the foreign output gap term if it may not be zero under certain cases. Second, the Phillips curve should include the first order of the relative price distortion as a linear term.

Appendix

A. Decentralization

Having described the optimal monetary policy in the non-cooperative case, the analysis of this section will discuss how the second-best allocation implied by the optimal monetary policy can be implemented in a decentralized economy. In particular, this section begins by investigating whether the optimal inflation rate described above is consistent with forward-looking price-setting equations of firms. It then moves on to the discussion of the magnitude of the subsidy for households, which makes the optimal allocation implementable in a decentralized economy.

Substituting (3.3) and (3.2) into (2.7), the definition of the producer price level implies that, under the optimal monetary policy, the relative price at period *t* of the new optimal price becomes

$$\frac{P^*_{H,t}}{P_{H,t}} = \frac{1}{\Delta_t}. \tag{A.1}$$

In order to compute the marginal cost that is implied by the optimal policy, it is useful to obtain the following recursive representations of I_t and K_t after substituting $Y_t P_{H,t} = C_t P_t$ into theses two equations:

$$I_t = \frac{\varepsilon}{\varepsilon - 1}\left(\frac{MC_t}{P_{H,t}}\right)U'(C_t)C_t + \alpha\beta E_t[\Pi^{\varepsilon}_{H,t+1} I_{t+1}], \tag{A.2}$$

$$K_t = U'(C_t)C_t + \alpha\beta E_t[\Pi^{\varepsilon-1}_{H,t+1} K_{t+1}], \tag{A.3}$$

where terminal conditions are

$$\lim_{T\to\infty}(\alpha\beta)^T E_t[\Pi^{\varepsilon-1}_{H,t+T} K_{t+T}] = 0, \ \lim_{T\to\infty}(\alpha\beta)^T E_t[\Pi^{\varepsilon}_{H,t+T} I_{t+T}] = 0.$$

Next, letting $Z_t = K_t - \Delta_t I_t$, substituting $\Delta_{t+1}/\Delta_t = \Pi_{H,t+1}$ into (A.2), multiplying Δ_t to the resulting equation and subtracting it from (A.3), one will have

$$Z_t = U'(C_t)C_t(1 - \frac{\varepsilon}{\varepsilon - 1}\frac{\Delta_t MC_t}{P_{H,t}}) + E_t[\Pi_{H,t+1}^{\varepsilon-1} Z_{t+1}]. \tag{A.4}$$

In addition, substituting (A.1) into the profit maximization condition (2.9) leads to $K_t = \Delta_t I_t$, which in turn implies that $Z_t = 0$. Thus, setting $Z_t = Z_{t+1} = 0$ in (A.4), one can see that under the optimal policy, the nominal marginal cost at period *t* turns out to be

$$MC_t = \frac{\varepsilon - 1}{\varepsilon}\frac{P_{H,t}}{\Delta_t}. \tag{A.5}$$

The analysis then turns to the discussion of the optimal subsidy rate that is implied by the optimal policy. Optimal tradeoff between consumption and leisure leads to $(1-\gamma)C_t / N_t = (1+\tau)W_t / P_t$. Thereby, setting $W_t = MC_t A_t$ in this equation implies that $(1-\gamma)C_t P_t = (1+\tau)MC_t A_t N_t$. Substituting (A.5) into this equation, with the aggregate production function (2.6), and plugging (2.10) into the resulting equation, one can show that the optimal subsidy rate is

$$1 + \tau = (1-\gamma)\frac{\varepsilon}{\varepsilon - 1}. \tag{A.6}$$

The magnitude of the subsidy rate specified in (A.6) is consistent with the one used in Gali and Monacelli (2002) and Clarida, Gali, and Gertler (2002).

The analysis that follows turns to the discussion of the behaviors of the terms of trade and the nominal exchange rate under the optimal policy. Notice that the terms of trade equals the ratio of the output level of the home country to that of the foreign country, as can be seen in (2.12). Therefore, dividing both sides of the first equation in (3.12) by the corresponding sides of the second equation in (3.12) and then combining the resulting equation with (3.5) after taking the logarithm, one can have

$$s_t = \kappa_s + (a_t + a_t^*) - (p_{H,t} - p_t^\circ) + (p_{F,t}^* - p_F^{*\circ}), \tag{A.7}$$

where $s_t = \log S_t$ and $\kappa_s = (1+\nu)^{-1}\log((1-\gamma)/\gamma)$.

Furthermore, the definition of the terms of trade, along with the law of one price, implies that the nominal exchange rate is given by $\varepsilon_t = S_t P_{H,t} / P_{F,t}^*$. Thus, taking the logarithm to both sides of this equation and substituting (A.8) into the resulting equation, it can be shown that the log level of the nominal exchange rate in the non-cooperative case, denoted by $e_t = \log\varepsilon_t$, becomes

$$e_t = \kappa_s + (a_t - a_t^*) + (p_H^\circ - p_F^{*\circ}). \tag{A.8}$$

In order to compute the consumer price index, notice that $P_t = \kappa^{-1} S_t^\gamma P_{H,t}$ in equilibrium. Let $\overline{P}_t$ denote the optimal consumer price level that would hold in the absence of an initial price dispersion in both of the two countries. Then, taking the logarithm to both sides of the equation explained above and substituting (A.8) into the resulting equation, the log-level of consumer price index at period *t* is

$$p_t = \overline{p}_t + (1-\gamma)p_{H,t} + \gamma p_{F,t}^* + \gamma(p_H^\circ - p_F^{*\circ}); \quad \overline{p}_t = \kappa_p + a_t - a_t^*, \tag{A.9}$$

where $p_t = \log P_t$, $\overline{p}_t = \log \overline{P}_t$, and $\kappa_p = \kappa_s - \log\kappa$. Note that the Euler equation is given by

$$\beta R_t E_t[(\frac{C_t}{C_{t+1}})^\sigma \frac{P_t}{P_{t+1}}] = 1, \tag{A.10}$$

where R_t is the (gross) nominal interest rate. Then, one can use equations (3.9) and (A.10) to show that the optimal rate of nominal interest in the non-cooperative case can be written as

$$r_t = \overline{r}_t + \nu(\eta_1(p_{H,t+1} - p_{H,t}) + \eta_2(p_{F,t+1}^* - p_{F,t}^*)), \tag{A.11}$$

where $r_t = \log R_t$ and $\overline{r}_t = \log \overline{R}_t$. Given the relationship between parameters σ and η_2 described above, equation (A.11) implies that as long as ν is positive, a rise in the foreign inflation rate raises the domestic nominal interest rate if $\sigma < 1$, while the domestic nominal interest rate falls if $\sigma > 1$.

B. Transition dynamics

In order to see how equilibrium dynamics evolve over time under the optimal and zero producer price inflation policies, it is necessary to assign numerical values to the parameters included in equilibrium conditions. In simulating the model, a log utility function for consumption and a quadratic function for the number of hours worked are chosen as a benchmark choice of preference parameter values, which corresponds to setting $\sigma = 1$ and $\chi = 1$. The value for the time-discount factor is given by $\beta = 0.99$, which corresponds to a real interest rate of about 4 percent per year. The demand elasticity is set to be $\varepsilon = 11$. In particular, since the aggregate markup, denoted by μ, is $\mu = \varepsilon/(\varepsilon - 1)$ at the steady state with zero inflation, setting $\varepsilon = 11$ amounts to setting $\mu = 1.1$. The value of α is set to be $\alpha = 0.75$, which implies that the average time duration of fixing prices is one year.

In generating transition dynamics, it is also assumed that the economy stays in a steady state with a positive long-run average inflation rate in the period before the central bank starts a monetary policy at period 0. In addition, the law of motion for the measure of relative price distortion (2.8) implies that the steady state level of relative price distortion is determined as follows:

$$\Delta = \frac{1-\alpha}{1-\alpha\Pi_H^{\varepsilon}}\left(\frac{1-\alpha\Pi_H^{\varepsilon-1}}{1-\alpha}\right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{B.1}$$

where Δ and Π denote the steady state values of the measure of relative price distortion and the inflation rate, respectively. It thus indicates that choosing a long-run average inflation rate corresponds to opting for a long-run average value of the measure of relative price distortion. As a benchmark choice, the initial level of the measure of relative price distortion is chosen to be consistent with a 2% annual average inflation rate.[10] This completes the description of a benchmark calibration, though the analysis also uses various sets of parameter values other than the benchmark calibration. The parameter values used in this paper are summarized in Table 1.

[Table 1] Parameter Values

Parameter	Values	Description and Definitions
α	[0.1, 0.75]	Fraction of firms that do not change in a period
π	$\frac{2}{400}$	Initial long-run average inflation rate
ε	[8, 20]	Elasticity of demand for differentiated goods
ν	[1, 5]	Inverse of elasticity of labor supply
σ	[1, 5]	Risk aversion parameter
β	0.99	Time discount factor (quarterly)
γ	0.5	Share of the home country

Figure 1 reports the equilibrium dynamics of output gap and inflation rate under the optimal and zero producer price inflation policies. Additionally, the transition dynamics that are obtained from the analytical solution to the original optimal policy problem are compared with those of the linear quadratic policy problem. Figure 1 indicates that they make little difference for the set of parameter values used in this paper. Figure 1 also demonstrates that under the two policies, the output ends up with at higher level than its initial level in the period before the central bank begins a monetary policy at period 0. However, it does not imply that the two policies always achieve disinflation without sacrificing output. Specifically, one can find a critical level of the steady state inflation rate that makes the steady state output gap negative if the steady state inflation rate is higher than the critical level and positive if it is lower than the critical level.[11]

[10] Equation (B.1) gives a sufficient condition for positive steady state prices: $\alpha\Pi^{\varepsilon} < 1$. This inequality is thus a constraint for a certain set of parameter values, as noted in King and Wolman (1999) and Ascari (2003).

[11] The steady state output gap is given by $x = \frac{\nu(1+\eta_1)}{1+\nu}\delta + \frac{(1+\eta_1)}{1+\nu}\hat{m}c_H - \frac{\nu\eta_2}{1+\nu}\delta^* = \frac{\eta_2}{1+\nu}\hat{m}c_F^*$ and the log deviation of the home country's real marginal cost is

C. The optimal monetary policy under cooperation

Under cooperation, the period objective function of the central banks in home and foreign countries becomes a weighted average of the period utility functions of the households in the two countries:

$$\Phi(C_t, N_t, N_t^*) = U(C_t) - (1-\gamma)V(N_t) - \gamma V(N_t^*), \tag{C.1}$$

where $\Phi(C_t, N_t, N_t^*)$ denotes the period objective function under cooperation.

Let $J^c(\Delta_{t-1}, \Delta_{t-1}^*, v_t, v_t^*)$ represent the value function at period t in the Bellman equation for the optimal policy problem under cooperation.[12] The optimal monetary policy under cooperation, then, solves the following optimization problem:

$$\begin{aligned} J^c(\Delta_{t-1}, \Delta_{t-1}^*, v_t, v_t^*) = \max\{&\Phi(C_t, N_t, N_t^*) \\ &+\beta E_t[J^c(\Delta_t, \Delta_t^*, v_{t+1}, v_{t+1}^*)]\} \end{aligned} \tag{C.2}$$

subject to

$$C_t = \kappa\left(\frac{A_t^*}{\Delta_t^*} N_t^*\right)^{\gamma} \left(\frac{A_t}{\Delta_t} N_t\right)^{1-\gamma}, \tag{C.3}$$

$$\Delta_t = (1-\alpha)\left(\frac{1-\alpha\Pi_{H,t}^{\varepsilon-1}}{1-\alpha}\right)^{\frac{\varepsilon}{\varepsilon-1}} + \alpha\Pi_{H,t}^{\varepsilon}\Delta_{t-1}, \tag{C.4}$$

$$\Delta_t^* = (1-\alpha^*)\left(\frac{1-\alpha^*(\Pi_{F,t}^*)^{\varepsilon-1}}{1-\alpha^*}\right)^{\frac{\varepsilon}{\varepsilon-1}} + \alpha^*(\Pi_{F,t}^*)^{\varepsilon}\Delta_{t-1}^*, \tag{C.5}$$

$\hat{m}c_H = \frac{1}{1-\varepsilon}\log\left(\frac{1-\alpha\Pi_H^{\varepsilon}}{1-\alpha}\right) + \log\left(\frac{1-\alpha\beta\Pi_H^{\varepsilon}}{1-\alpha\beta\Pi_H^{\varepsilon-1}}\right)$. Thus, the partial derivative of the steady state output gap with respect to inflation rate at zero inflation rate is $\frac{\partial x}{\partial \pi_H} = \frac{(1+\eta_1)}{1+\nu}\frac{\alpha(1-\beta)}{(1-\alpha)(1-\alpha\beta)}$, where $\pi_H = \log\Pi_H$. It means that the steady state output gap falls as the steady state inflation rate falls to the neighborhood of zero inflation rate, if $\frac{(1+\eta_1)}{1+\nu} > 0$.

[12] Clarida, Gali, and Gertler (2002) analyze the optimal monetary policy problem under cooperation on the basis of a loss function obtained from a quadratic approximation to the welfare function (C.1) and from forward-looking Phillips curves in home and foreign countries.

taking as given initial values for the measure of relative price distortion Δ_{-1}, Δ^*_{-1}, and state vectors $\{v_t, v^*_t\}_{t=0}^{\infty}$. The first-order conditions for consumption and labor can be summarized as follows:

$$U'(C_t)C_t = V'(N_t)N_t = V'(N^*_t)N^*_t . \tag{C.6}$$

The first-order conditions for domestic and foreign relative price distortions can be written as

$$\omega_t = \frac{Y_t}{\Delta_t}U'(C_t) + \alpha\beta E_t[\Pi^{\varepsilon}_{H,t+1}\omega_{t+1}], \tag{C.7}$$

$$\omega^*_t = \frac{Y^*_t}{\Delta^*_t}U'(C^*_t) + \alpha^*\beta E_t[\Pi^{*\varepsilon}_{F,t+1}\omega^*_{t+1}], \tag{C.8}$$

where ω_t and ω^*_t denote the Lagrange multipliers for constraints (C.4) and (C.5) in period *t*, respectively. The first-order condition for domestic and foreign producer price inflation rate can be written as

$$\left(\frac{1-\alpha\Pi^{\varepsilon-1}_{H,t}}{1-\alpha}\right)^{\frac{\varepsilon}{\varepsilon-1}} = \Pi^{\varepsilon}_{H,t}\Delta_{t-1}, \tag{C.9}$$

$$\left(\frac{1-\alpha^*(\Pi^*_{F,t})^{\varepsilon-1}}{1-\alpha^*}\right)^{\frac{\varepsilon}{\varepsilon-1}} = \Pi^{\varepsilon}_{F,t}\Delta^*_{t-1} . \tag{C.10}$$

The efficiency condition under monetary cooperation does not include the shares of population as can be seen in (C.6), unlike the non-cooperative case. It in turn makes the optimal subsidy rate for households in the non-cooperative case differ from that under monetary cooperation. Specifically, the following equation for the subsidy rate holds under cooperation: $1+\tau = \varepsilon/(\varepsilon-1)$, which implies that the optimal subsidy rate under cooperation eliminates only the distortion associated with imperfect competition in the goods market.

As before, the analysis of this section focuses on the functional form of utility function specified in (3.6), in order to compute a closed-form solution for equilibrium. The output gap under cooperation is identical to that in the non-cooperative case, though the natural level of output under cooperation differs from that of the non-cooperative case. The aggregate outputs in the cooperative case are given by

$$\tilde{Y}_t = \tilde{\kappa}_n (\frac{A_t}{\Delta_t})^{1+\eta_1} (\frac{A_t^*}{\Delta_t^*})^{\eta_2} \; ; \; \tilde{Y}_t^* = \tilde{\kappa}_n (\frac{A_t}{\Delta_t})^{\eta_1} (\frac{A_t^*}{\Delta_t^*})^{1+\eta_2} \, . \tag{C.11}$$

It also follows from (C.11) that the natural level of output under cooperation can be written as

$$\bar{\tilde{Y}}_t = \tilde{\kappa}_n (\frac{A_t}{\Delta_t})^{1+\eta_1} (\frac{A_t^*}{\Delta_t^*})^{\eta_2} \; ; \; \bar{\tilde{Y}}_t^* = \tilde{\kappa}_n A_t^{*1+\eta_2} A_t^{\eta_1} \, , \tag{C.12}$$

where $\bar{\tilde{Y}}_t$ denotes the natural level of domestic output under cooperation and $\bar{\tilde{Y}}_t^*$ denotes the natural level of foreign output under cooperation. Looking at equations (3.13) and (C.12), one can see that the natural level of output under cooperation is proportional to that in the non-cooperative case. Then, taking the logarithm to both sides of (C.11) and (C.12) and combining the resulting equations, one can see that domestic and foreign output gaps under cooperation become

$$\tilde{x}_t = -(1+\eta_1)\delta_t - \eta_2 \delta_t^* \; ; \; \tilde{x}_t^* = -\eta_1 \delta_t - (1+\eta_2)\delta_t^* \, , \tag{C.13}$$

where $\tilde{x}_t$ denotes the domestic output gap under cooperation and $\tilde{x}_t^*$ denotes the foreign output gap under cooperation. Note that the logarithm of relative price distortion can be written as log-deviation of the producer price level from its target, as can be seen in (3.5) and its foreign analog. In addition, relative price distortion has identical values in both non-cooperative and cooperative cases, given the same initial values of Δ_{-1} and Δ_{-1}^*. Thus, the following relationship between output gap and the producer price index holds:

$$\tilde{x}_t = -(1+\eta_1)(p_{H,t} - p_H^{\circ}) - \eta_2 (p_{F,t}^* - p_F^{*\circ}) \, , \tag{C.14}$$

$$\tilde{x}_t^* = -\eta_1 (p_{H,t} - p_H^{\circ}) - (1+\eta_2)(p_{F,t}^* - p_F^{*\circ}) \, . \tag{C.15}$$

Comparing (C.14) and (C.15) with (3.16) and (3.17), one can see that the optimal monetary policy rules under cooperation are identical to those in the non-cooperative case, though the natural levels of output in the two cases are not the same.

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