The relationship between reciprocal currency futures prices

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Abstract

Consider a futures contract on Country 2's currency denominated in Country 1's currency, and its reciprocal, a futures contract on Country 1's currency denominated in Country 2's currency. Because both are marked to market in different currencies, the relationship between the associated futures prices is not simple. We investigate the functional relationship between these two futures prices.

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1 Introduction

Consider two currencies, in “Country 1” and “Country 2”, and consider the Country 1 $T$-expiration forward contract on one unit of Country 2's currency, and the Country 2 $T$-expiration forward contract on one unit of Country 1's currency. Let $G(t;T)$ and $\Gamma(t;T)$ be the respective time-$t$ forward prices, denominated in the respective currencies. Then it is an elementary result that if there is no arbitrage and markets are frictionless, we must have

$$G(t;T) = 1/\Gamma(t;T).$$

Now suppose, instead, that we are interested in the two futures prices. Unlike forward contracts, the two futures contracts are marked-to-market in the two respective currencies. Let $H(t;T)$ and $\eta(t;T)$ be the time-$t$ $T$-expiration Country 1 and Country 2 futures prices, respectively. Again, the underlying for each one is the other country's currency. What is the relationship between $H(t;T)$ and $\eta(t;T)$? This is a question which can be posed in an undergraduate class. The answer, however, is not elementary.

As it is well known, if interest rates are deterministic, futures prices are equal to the corresponding forward prices. (See Cox, Ingersoll and Ross (1981), Jarrow and Oldfield (1981).) Then, based on (1),

$$H(t;T) = 1/\eta(t;T).$$

However, if interest rates are stochastic, a futures price and its corresponding forward price need not be equal. The objective of this paper is to find a relationship between currency futures prices which generalizes (2). We will give sufficient conditions for a relationship of the form

$$H(t;T) = f(\eta(t;T), t),$$

where $f$ is a two-variable real function. In particular, as we will see, the special case (2) holds under conditions which are more general than deterministic interest rates.

We proceed as follows: Section 2 elaborates on the notation and on some preparations. In Section 3 we discuss a setting where in each country there is a simple futures-forward relationship, and as a result the relationship between the futures prices $H$ and $\eta$ is of the form $H = h(t)/\eta$. An example with $h \neq 1$ is presented in a setting of a two-country Vasicek-type model. In Section 4 we switch to a more general relationship of the form (3), which is obtained under assumptions concerning certain covariances. Section 5 includes a discussion and a short summary.

2 Notation and some preparations

We consider a two country frictionless financial market. The currencies in Country 1 and Country 2 are “dollar” and “drachma”, respectively. We will use the following notation. (Later we may omit the dependence on $T$, which is fixed.)

$X(t)$ Spot price in dollars of one drachma.

-1-
\( \xi(t) \) Spot price in drachmas of one dollar.

\( H(t; T) \) Dollar-denominated \( T \)-expiration time-\( t \) futures price of one drachma.

\( \eta(t; T) \) Drachma-denominated \( T \)-expiration time-\( t \) futures price of one dollar.

\( G(t; T) \) Dollar-denominated \( T \)-expiration time-\( t \) forward price of one drachma.

\( \Gamma(t; T) \) Drachma-denominated \( T \)-expiration time-\( t \) forward price of one dollar.

\( r(t) \) Dollar-denominated short rate.

\( \rho(t) \) Drachma-denominated short rate.

\( B(t; T) \) Time-\( t \) value in dollars of a \( T \)-maturity zero-coupon bond paying one dollar.

\( \beta(t; T) \) Time-\( t \) value in drachmas of a \( T \)-maturity zero-coupon bond paying one drachma.

At time \( T \) we have

\[
H(T; T) = G(T; T) = X(T), \quad \eta(T; T) = \Gamma(T; T) = \xi(T).
\]

(4)

The spot prices are related via

\[
X(t) = 1/\xi(t).
\]

(5)

Relationship (1) between the forward prices follows from (5) and from the well-known interest rate parity relationship in each country:

\[
G(t; T) = X(t) \frac{\beta(t; T)}{B(t; T)}, \quad \Gamma(t; T) = \xi(t) \frac{B(t; T)}{\beta(t; T)}.
\]

(6)

We assume a continuous-time financial market, where all relevant state variables are \( \text{Ito processes on the time interval } [0, T] \), defined on some filtered probability space \((\Omega, \mathcal{F}, \{\mathcal{F}_t\}, P)\). In general, if \( Y \) and \( Z \) are two \( \text{Ito processes, then the product } dY \, dZ \text{ will be used as an informal notation for } d\langle Y, Z \rangle \), where \( \langle Y, Z \rangle \) is the square-bracket process. If \( dY(t) = \mu_Y(t) dt + \sum_i \sigma_{Y,i}(t) \, dW_i(t) \) where each \( W_i \) is a standard Brownian motion, and if \( dZ \) has a similar expansion, then \( dY \, dZ \) is just the formal product of the two summations, using the well-known multiplication rules for \( \text{Ito's differentials. See, e.g., Duffie (2001) or Musiela and Rutkowski (2005) for definitions and technical conditions.} \)

The product rule and the quotient rule from \( \text{Stochastic Calculus} \) give the following results, which are needed later in the paper. We use an abbreviated notation.

\[
\frac{d\xi}{\xi} = - \frac{dX}{X} + \left( \frac{dX}{X} \right)^2.
\]

(7)

\footnote{We note parenthetically that, in fact, Eq (1) can be proved directly “by arbitrage,” using a position which includes only the two forward contracts: Indeed, consider the following strategy: (i) At time \( t \), enter into a forward contract to convert one dollar into \( \Gamma(t; T) \) drachmas at time \( T \), and (ii) also enter into a second forward contract to convert \( \Gamma(t; T) \) drachmas at time \( T \) to \( \Gamma(t; T) \cdot G(t; T) \) dollars. Thus the cash flow at time \( t \) is zero, while the cash inflow at time \( T \), in dollars, is \( -1 + \Gamma(t; T) \cdot G(t; T) \). If there is no arbitrage, this deterministic cash flow should be zero.}
\[ \frac{dG}{G} = \frac{dX}{X} + \frac{d\beta}{\beta} - \frac{dB}{B} + \frac{dX}{X} \cdot \frac{d\beta}{\beta} + \frac{(dB)^2}{B^2} - \frac{d\beta dB}{B} - \frac{dX dB}{X B}. \]  

(8)

\[ \frac{dG}{G} \frac{dB}{B} = \left( \frac{dX}{X} + \frac{d\beta}{\beta} - \frac{dB}{B} \right) \frac{dB}{B}. \]  

(9)

\[ \frac{d\Gamma}{\Gamma} \frac{d\beta}{\beta} = \left( \frac{d\xi}{\xi} + \frac{dB}{B} - \frac{d\beta}{\beta} \right) \frac{d\beta}{\beta} = - \left( \frac{dX}{X} + \frac{d\beta}{\beta} - \frac{dB}{B} \right) \frac{d\beta}{\beta}. \]  

(10)

\[ \frac{dG}{G} \frac{dB}{B} + \frac{d\Gamma}{\Gamma} \frac{d\beta}{\beta} = \frac{dG}{G} \left( \frac{dX}{X} - \frac{dG}{G} \right) = - \frac{d\Gamma}{\Gamma} \left( \frac{dX}{X} + \frac{d\Gamma}{\Gamma} \right). \]  

(11)

Informally, (8) multiplied by \( dB/B \) gives (9). Eq. (10) is obtained by symmetry, and in the second equality we employ (7). The first equality in Eq. (11) is obtained by adding (9) and (10), then using the fact (from ((8))) that \( dB/B - d\beta/\beta = dX/X - dG/G + (\ldots) \). The second equality in Eq. (11) is obtained by symmetry.

Next, as a preparation for Section 4 which contains the main results, let us define a certain trading strategy. Suppose \( \lambda = \{\lambda(t); t \in [0,T]\} \) is a given Ito process. “Strategy \( S_{2,1}(\lambda) \)” is defined as follows:

\( S_{2,1}(\lambda): \) At any time \( t \), hold \( \lambda(t) \) drachma-denominated \( T \)-expiration futures contracts (each on one dollar). Continuously convert the marking-to-market profits into dollars and withdraw them.\(^2\)

We recall that a futures contract as above has zero value (“ex-payouts”) all the time and (informally) it generates an incremental cash flow (from “marking-to-market”) over \([t, t+dt]\) equal to \( d\eta(t) \) drachmas. Thus the above dynamic portfolio has zero value at any time (“immediately after the revision”). The cumulative cash flow in dollars over \([0, t]\) to be denoted \( \Phi_{2,1}(t; \lambda) \), satisfies

\[ d\Phi_{2,1}(t; \lambda) = \lambda(t)X(t) \, d\eta(t)[1 + dX(t)/X(t)]. \]  

(12)

This is because the strategy generates an incremental cash flow of \( \lambda(t) \, d\eta(t) \) drachmas over the interval \([t, t+dt]\), which is then converted into \( \lambda(t) \, d\eta(t)X(t+dt) \) dollars, namely into \( \lambda(t) \, d\eta(t) \{X(t) + dX(t)\} \) dollars.

Likewise, we can define “Strategy \( S_{1,2}(\lambda) \)” as follows:

\( S_{1,2}(\lambda): \) At any time \( t \), hold \( \lambda(t) \) dollar-denominated \( T \)-expiration futures contracts (each on one drachma). Continuously convert the marking-to-market profits into drachmas and withdraw them.

\(^2\)To clarify: Negative \( \lambda \) means a short position. Negative marking-to-market proceeds are financed by converting dollars into to drachmas. Note that the definition does not specify what is done with the dollar cash flow generated by the strategy. It does not matter if it is invested (or borrowed) in a specified fashion or used to increase (or decrease) consumption.
The cumulative cash flow in drachmas over \([0, t]\) will be denoted \(\Phi_{1,2}\). Then
\[
d\Phi_{1,2}(t; \lambda) = \lambda(t)\xi(t) \, dH(t)[1 + \, d\xi(t)/\xi(t)].
\] (13)

3 A consequence of a forward-futures relationship

As it was pointed out in the introduction, if interest rates in the two countries are deterministic, then futures prices in the two countries are equal to the corresponding forward prices, and thus the relationship \(G(t; T) \cdot \Gamma(t; T) = 1\) translates to \(H(t; T) \cdot \eta(t; T) = 1\). In this section we will analyze a case where \(H \cdot \eta\) need not be equal to 1, but it will still be a deterministic function of \(t\).

**Proposition 3.1:** With assumptions and notations as in Section 2, suppose that
\[
dG(t; T) \, dB(t; T) \over G(t; T) \, B(t; T) = \chi_{G,B}(t; T) \, dt,
\] (14)
\[
d\Gamma(t; T) \, d\beta(t; T) \over \Gamma(t; T) \, \beta(t; T) = \chi_{\Gamma,\beta}(t; T) \, dt,
\] (15)
where \(\chi_{G,B}(t; T)\) and \(\chi_{\Gamma,\beta}(t; T)\) are deterministic continuous functions of \(t\). Then:

(a) The Country 1 and Country 2 futures-forward relationships are, respectively,
\[
H(t; T) = G(t; T) \exp \left( - \int_t^T \chi_{G,B}(u; T) \, du \right),
\] (16)
\[
\eta(t; T) = \Gamma(t; T) \exp \left( - \int_t^T \chi_{\Gamma,\beta}(u; T) \, du \right).
\] (17)

(b) As a result, the relationship between the two futures prices \(H\) and \(\eta\) is
\[
H(t; T) \cdot \eta(t; T) = \exp \left( - \int_t^T [\chi_{G,B}(u; T) + \chi_{\Gamma,\beta}(u; T)] \, du \right).
\] (18)

**Proof:** For contracts on one drachma, Eq. (16) is the futures-forward relationship, under the assumption (14). This relationship is derived in Jamshidian (1993), Proposition 1.1, with arbitrary underlying security. (A more direct proof, based on replication of a futures contract, is available from the author.) Eq. (17) is the Country 2 analog, where the contracts are on one dollar. Because \(G \cdot \Gamma = 1\), Eq. (18) follows.

**Note:** We will need this later: Under the assumptions of Proposition 3.1, and the implied relationship (17), it follows that another representation of the integrand from (18) is as follows:
\[ \chi_G, B dt + \chi_{\Gamma, \beta} dt = - \left( \frac{d\eta}{\eta} \cdot \frac{dX}{X} + \frac{(d\eta)^2}{\eta^2} \right). \]  

(19)

An outline of the proof: Eq. (17) entails that \( d\eta/\eta = d\Gamma/\Gamma + (\ldots) dt \). This means that the RHS of (19) will remain the same if we replace \( \eta \) by \( \Gamma \). Now refer to Eq. (11).

Next, in order to provide an example for Proposition 3.1, let us consider a three-state-variable model where the exchange rate is a geometric Brownian motion and in each country the term structure of interest rates is like in Vasicek (1977). (The latter is only for concreteness, and in fact other one-factor models can be used.) It can be shown that such a unified arbitrage-free setting can be defined. (A proof is available from the author.) The model can be specified with the following structure:

(V.1) The instantaneous interest rates in the two countries satisfy

\[ (dr(t))^2 = \sigma_1^2 dt, \quad (d\rho(t))^2 = \sigma_2^2 dt, \quad dr(t) \cdot d\rho(t) = \zeta_{1,2} \sigma_1 \sigma_2 dt, \]  

(20)

where \( \sigma_1 > 0, \sigma_2 > 0 \) and \( \zeta_{1,2} \) are constants.

(V.2) The time-\( t \) prices of the \( T \)-expiration zero-coupon bonds in the two countries are of the form (taking \( T \) as fixed)

\[ \frac{dB(t; T)}{B(t; T)} = (\ldots) dt - b_1(t; T) dr(t), \]  

(21)

\[ \frac{d\beta(t; T)}{\beta(t; T)} = (\ldots) dt - b_2(t; T) d\rho(t), \]  

(22)

where \( b_1 \) and \( b_2 \) are deterministic functions of \( t \).

(V.3) The exchange rate process \( \{X(t)\} \) satisfies

\[ \left( \frac{dX(t)}{X(t)} \right)^2 = \sigma_3^2 dt, \]  

(23)

\[ dr(t) \cdot \frac{dX(t)}{X(t)} = \zeta_{1,3} \sigma_1 \sigma_3 dt, \quad d\rho(t) \cdot \frac{dX(t)}{X(t)} = \zeta_{2,3} \sigma_2 \sigma_3 dt, \]  

(24)

where \( \sigma_3, \zeta_{1,3} \) and \( \zeta_{2,3} \) are constants.

Next, we use Eqs. (9) and (10) to obtain

\[ \frac{dG(t; T)}{G(t; T)} \frac{dB(t; T)}{B(t; T)} = - b_1 \{ \zeta_{1,3} \sigma_1 \sigma_3 - b_2 \zeta_{1,2} \sigma_1 \sigma_2 + b_1 \sigma_1^2 \} dt, \]  

(25)

\[ \frac{d\Gamma(t; T)}{\Gamma(t; T)} \frac{d\beta(t; T)}{\beta(t; T)} = - b_2 \{ \zeta_{2,3} \sigma_2 \sigma_3 - b_1 \zeta_{1,2} \sigma_1 \sigma_2 + b_2 \sigma_2^2 \} dt. \]  

(26)

These are (14)-(15) in our case. The rest is a matter of Calculus work, requiring the specification of the functions \( b_1 \) and \( b_2 \). The details are available from the author. They are not
really needed in order to be convinced, based on (25)-(26), that the RHS of (18) is a function of $t$ which is not identically equal to 1.

4 Relying on the dynamics of the futures price $\eta$

Recall that $H$ and $\eta$ are the two reciprocal futures prices. In this section we investigate the possibility that the relationship between them is of the form $H(t; T) = f(\eta(t); T), t)$ (more compactly, $H(t) = f(\eta(t), t)$, suppressing the dependence on $T$). We will use

**Condition (A):**

\[
\frac{d\eta(t)}{\eta(t)} \cdot \frac{dX(t)}{X(t)} = c(\eta(t), t) \, dt, \quad \text{or equivalently} \quad \frac{d\eta(t)}{\eta(t)} \cdot \frac{d\xi(t)}{\xi(t)} = -c(\eta(t), t) \, dt, \tag{27}
\]

and

\[
\frac{(d\eta(t))^2}{\eta^2(t)} = v^2(\eta(t), t) \, dt,
\tag{28}
\]

where $c, v^2 : (0, \infty) \times [0, T] \to \mathbb{R}$ are suitably well-behaved functions.

It is natural to start with necessary conditions:

**Proposition 4.1:** Suppose Condition (A) holds. Suppose the relationship between the two futures prices is $H(t) = f(\eta(t), t)$, for some suitably smooth $f : (0, \infty) \times [0, T] \to \mathbb{R}$, expressed as $f(\eta, t)$.\(^3\) Then necessarily we must have

\[
f_i(\eta, t) + \frac{1}{2} \eta^2 v^2(\eta, t) f_{yy}(\eta, t) - \eta c(\eta, t) f_y(\eta, t) = 0, \tag{29}
\]

\[
f(\eta, T) = 1/\eta. \tag{30}
\]

**Proof:** Consider the trading strategy $S_{1,2}(\lambda)$ as in Section 2, taking $\lambda(t) = 1/\xi(t)$ in our case. Then the (drachma) cumulative cash flow $\Phi_{1,2}(t; \lambda)$ satisfies (13). Using abbreviated notation (where $f$ and its derivatives are evaluated at $(\eta(t), t)$), the equation translates to

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\(^3\)Based on (7).

\(^4\)Caution: To avoid excess notation, following a common practice in the literature, the role of the notation $\eta$ depends on the context. In $f(\eta, t)$, $\eta$ is a “dummy parameter” (variable) in the sense of Calculus, whereas the notation $f(\eta(t), t)$ refers to the composite stochastic process obtained by substituting the stochastic process $\eta(t)$ instead of the variable $\eta$. Subscripts denote partial derivatives of $f(\eta, t)$. The notation $f_y(\eta(t), t)$ means: Evaluate the real function $\partial f/\partial \eta$ at $\eta = \eta(t)$. Likewise for $f_t$ and $f_{yy}$. 
\[
d\Phi_{1,2}(t; \lambda) = \left\{ f_\eta d\eta + f_t dt + \frac{1}{2} f_{\eta\eta}(d\eta)^2 \right\} (1 + d\xi/\xi)
\]
\[
= f_\eta d\eta + f_t dt + \frac{1}{2} f_{\eta\eta}(d\eta)^2 + f_\eta d\eta \frac{df}{\xi},
\]
\[
= f_\eta d\eta + \left( f_t + \frac{1}{2} \eta^2 f_{\eta\eta} v^2 - \eta f_\eta c \right) dt,
\]
(31)

where in the first equality we substituted \( \lambda \) and the Ito's expansion of \( dH(t) = df(\eta(t), t) \), and in the second equality we opened the brackets, neglecting high-order terms. In the third equality we substituted Condition (A). The equation says that if we apply strategy \( S_{1,2} \) as above and at the same time we hold \(-f_\eta(\eta(t), t)\) drachma-denominated futures contracts (on one dollar), then the incremental (drachma) cash flow \( d\Phi_{1,2} - f_\eta d\eta \) is of the form \{…\}dt. For a zero-value strategy, this is inconsistent with no-arbitrage, unless \( dt \)-coefficient is zero. This gives Eq. (29). ■

**Corollary 4.2:** Suppose Condition (A) holds. Suppose the relationship between the two futures prices is \( H(t) = f(\eta(t), t) \), where \( f(\eta, t) = \exp(\varphi(t))/\eta \) and where \( \varphi : [0, T] \to \mathbb{R} \) is a continuously differentiable function such that \( \varphi(T) = 0 \). Then necessarily

\[
c(\eta, t) + v^2(\eta, t) = -\varphi'(t).
\]
(32)

In particular, if \( f(\eta, t) = 1/\eta \) (in analogy to forward prices), then necessarily

\[
c(\eta, t) = -v^2(\eta, t)
\]
(33)

**Proof:** Substitute \( f(\eta, t) = \exp(\varphi(t))/\eta \) in (29). ■

The following result says that the converse of Proposition 4.1 is also true: The solution \( f \) of the PDE provides the link between the two futures prices. Furthermore, in analogy to option replication results, the proposition will provide the recipe for replicating a foreign currency futures contract (in the sense of matching cumulative cash flows) by using its reciprocal futures contract.

**Proposition 4.3** Suppose Condition (A) holds. Suppose \( f : (0, \infty) \times [0, T] \to \mathbb{R} \) is a suitably smooth function satisfying the PDE (29)-(30). Then

(a) The dollar-denominated futures price \( H(t) \) (with the boundary condition \( X(T) = 1/\eta(T) \)) must satisfy

\[
H(t) = f(\eta(t), t).
\]
(34)

(b) This can be derived as a result of “futures replication”: The zero-value trading strategy \( S_{2,1}(\lambda) \) (trading the drachma-denominated futures contract), with number-of-contracts equal to

\[
\lambda(t) := f_\eta(\eta(t), t)/X(t),
\]
(35)

generates cumulative cash flow \( \Phi_{2,1}(t; \lambda) \) (in dollars) satisfying

\[
d\Phi_{2,1}(t; \lambda) = df(\eta(t), t).
\]
(36)
Proof: Consider the Strategy $S_{2,1}(\lambda)$ from part (b) (as defined in Section 2). Based on (12), it generates a cumulative (dollar) cash flow stream $\Phi_{2,1}(t; \lambda)$ satisfying

$$d\Phi_{2,1}(t; \lambda) = f_\eta(\eta(t), t) d\eta(t)[1 + dX(t)/X(t)]$$
$$= f_\eta(\eta(t), t) d\eta(t) + f_\eta(\eta(t), t) \eta(t) c dt$$
$$= f_\eta(\eta(t), t) d\eta(t) + \left\{ f_t(\eta, t) + \frac{1}{2} \eta^2 \nu^2(\eta, t) f_{\eta\eta}(\eta, t) \right\} dt$$
$$= df(\eta(t), t),$$

(37)

where in the second equality we used Condition (A), in the third equality we used the PDE relationship and in the fourth equality we applied Ito's lemma. This proves Eq. (36). To interpret it, we can write

$$\Phi_{2,1}(T; \lambda) - \Phi_{2,1}(t; \lambda) = f(\eta(T), T) - f(\eta(t), t) = 1/\eta(T) - f(\eta(t), t).$$

(38)

We may think about the zero-value strategy $S_{2,1}(\lambda)$ as a dollar-denominated “synthetic futures contact” whose time-$T$ terminal condition is $1/\eta(T) = X(T)$ and its time-$t$ futures price is $f(\eta(t), t)$. Since the dollar-denominated futures contract (on one drachma) has the same terminal condition, its associated futures price $H(t, T)$ should be equal to $f(\eta(t), t)$. Bick (2011) elaborates on this approach for futures pricing. $\blacksquare$

The converse of Corollary 4.2 is as follows:

Corollary 4.4: Suppose Condition (A) holds. Suppose further that $k := c(\eta, t) + \nu^2(\eta, t)$ is a deterministic continuous function of $t$, and let

$$\varphi(t) = \int_t^T k(u) du.$$  

(39)

Then the results of Proposition 4.3 hold with

$$f(\eta, t) = \frac{1}{\eta} \exp(\varphi(t)).$$  

(40)

In particular, if $k = 0$ then $f(\eta, t) = 1/\eta$.

Notes:

1. Condition (33) can be written as

$$d\eta(t)/\eta(t) \cdot dX(t)/X(t) = -(d\eta(t))^2/\eta^2(t).$$  

(41)

The result of the second part of Corollary 4.4, namely $H\eta = 1$, is symmetric in the two currencies. It is clear, therefore, that the above condition can be replaced by

$$dH(t)/H(t) \cdot d\xi(t)/\xi(t) = -(dH(t))^2/H^2(t).$$  

(42)
or by (using (7))

\[
\frac{dH(t)}{H(t)} \cdot \frac{dX(t)}{X(t)} = \frac{(dH(t))^2}{H^2(t)}.
\] (43)

2. If the assumptions of Proposition 3.1 are satisfied, then the assumptions of Corollary 4.4 are also satisfied. This is clear from the note in Section 3. Obviously, regardless of the point of departure, the conclusion is the same.

5 Summary

While the relationship between the reciprocal forward prices is simple, the relationship between the reciprocal futures prices is not. In this paper we analyze a functional relationship between these two futures prices, which occurs under rather restricted assumptions ("Condition A"). We recognize that these assumptions need not be satisfied in general, and thus the relationship between the two futures prices can be more complex.

References


