Currency Returns in Different Time Zones

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June 12, 2015

ABSTRACT

I document the pattern of currency returns in different time zones. European currencies on average appreciate against the dollars during US business hours and depreciate during European business hours. The divergence generates a profitable intraday trading strategy. I offer an explanation based on market segmentation and exporters' trading pattern. The exporters from different time zones are unable to trade currencies directly with each other due to market segmentation in the time dimension. They rely on the financial intermediary to carry the currency positions from day to night. The financial intermediary charges a risk premium for its service, forcing the foreign currency to appreciate during home business hours.

Keywords: Exchange Rate Dynamics; Market Microstructure; Segmented Markets.

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This paper studies the intraday dynamics of exchange rates. Consider the EUR/USD pair for example. US exporters sell goods directly to European markets and earn Euros, and European exporters earn dollars in United States. Both parties need to sell the foreign currencies they earn from the overseas product markets. In a frictionless market they would like to trade with each other directly since the US exporters sell Euros/buy dollars while the European exporters sell dollars/buy Euros. But the foreign exchange markets are segmented in the time dimension: When the US exporters are in their business hours, the European exporters are sleeping. As a result, exporters on each side face insufficient interest from the long side in the foreign exchange market. Financial intermediation is required to transfer the currency position from day to night, and exporters need to offer price concession for offloading foreign exchange risk to the financial intermediary. This mechanism results in foreign currency appreciation during local business hours. To the author's best knowledge, this paper is the first to argue such friction affects the foreign exchange markets and gives rise to an economically meaningful pattern in the data.

Ranaldo (2009) documents that currencies tend to depreciate during home business hours and appreciate during foreign business hours in a sample before 2007. Using interbank FX market data from 2007 to 2014, I confirm that the Euros, British Pounds and Swiss Francs consistently appreciate against dollars during US business hours, i.e. from 4 PM London time to 5 PM New York time, and depreciate during Europe business hours, i.e. from 8 AM to 4 PM at London time. As shown in the left panel of Figure 1, while the EUR/USD[1] exchange rate (the grey line) has not moved much since 2007, a long position on Euros during US business hours produces large profits (the blue line), and a long position on Euros during EU business hours produces large losses[2] (the green line).

I extend the finding of Ranaldo (2009) by studying the trading strategy that longs Euros during US business hours and shorts Euros during EU business hours on the same day (henceforth the long-short strategy). Its performance is plotted in the right panel of Figure 1. After I account for the transaction cost, I find that this strategy has annualized sharpe ratio of 79%, larger than the stock return's sharpe ratio 29% over the same period. The strategy also has diversification benefits because its return is uncorrelated to stock market performance, central bank announcement dates and nonfarm payroll release dates. In addition, I find the mean and volatility of the return are higher when the volatility of the underlying exchange rate rises in the near past. This relationship suggests a risk-based explanation.

Summarizing the story and the empirical findings, I develop an equilibrium model of exchange rate dynamics. In the model, there are two types of market participants: speculators and hedgers. Speculators trade in each trading session, and US and EU hedgers sell foreign currencies in different trading sessions. The key friction is market segmentation between the hedgers in different time zones. Trading to maximize expected utility, the speculators effectively act as the financial intermediary that overcomes the market segmentation for the hedgers. In equilibrium, they carry

[1] I use EUR/USD pair for illustration. The results throughout this paper also apply to the GBP/USD and CHF/USD pairs.

[2] Alternative definitions of business hours produce similar results.

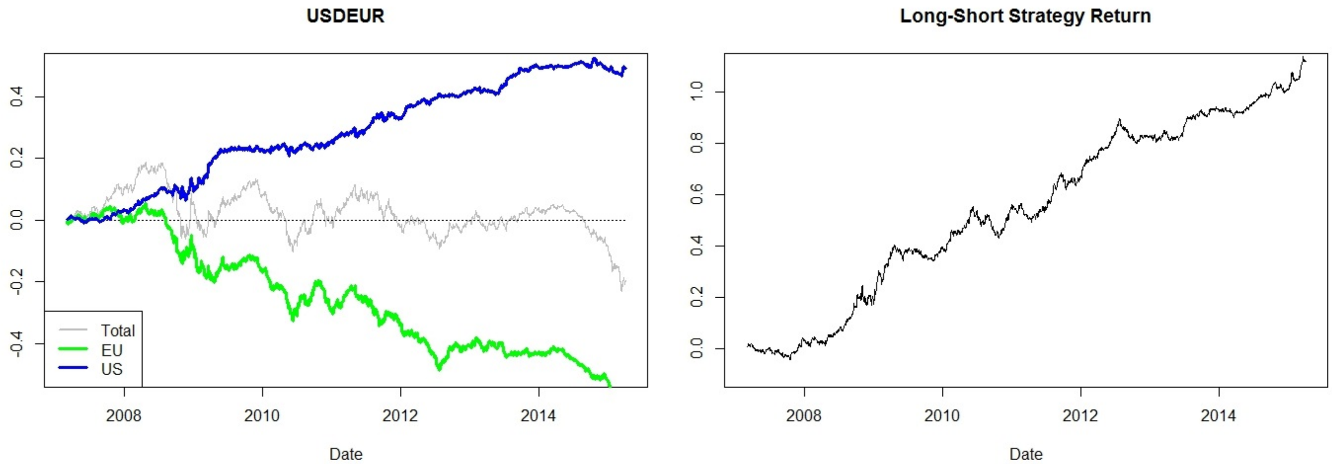

Figure 1. Exchange Rate Movement in Different Trading Sessions. The left panel plots the cumulative EUR/USD movement during European and US business hours. The right panel plots the cumulative return of the long-short strategy. The returns are presented in log units, and transaction cost is ignored.

the currency exposure to the next period and charge a risk premium for this service.

The model predicts that the exchange rate is a sum of two parts. One part is an alternating level factor and the other part is an AR(1) process. The level part has two constant levels, alternating between the US and EU business hours. It induces the Euros to appreciate during US business hours and depreciate during EU business hours by the same amount. Consistent with the data, this part implies that the return divergence between the US and EU business hours is not correlated with the macroeconomic shock. The AR(1) process represents the cumulative macroeconomic shock that affects the exchange rate, which has unconditional mean of 0 but it is highly persistent. It implies the autocorrelations of daily exchange rates are decaying exponentially from 1, which is also consistent with the data.

Finally, I use the method of moments to estimate the primitive parameters. I show that the estimated values are reasonable and the model's prediction matches key econometric characteristics of the realized exchange rate dynamics.

Literature Review:

The most related paper is Ranaldo (2009), which documents the time-of-day pattern of the exchange rates. Ranaldo (2009) explains this pattern with a liquidity story. He argues that domestic agents are net buyers of foreign currencies and they mainly trade at home business hours. The prevalence of domestic traders during home business hours bids up the price of forieng currencies. I give a completely different explanation based on market segmentation, which provides an economic foundation for the source of the order flow imbalance.

My model is along the line of using demand and supply to explain exchange rate dynamics. Explaining price movement by order flow is inherently incomplete if the origin of order flow is not understood. Recent years see a tendency towards examining the supply and demand as the fundamental driver of order flow. Blanchard, Giavazzi, and Sa (2005) and Hau and Rey (2006) derive foreign exchange market equilibrium based on changes in cross-country investment in financial assets. The demand-and-supply is determined by exporters (noise traders) and speculators in my model, which is a direct extension of the standard noise trader models such as Shiller (1984) and Osler (1995).

This paper provides a specific mechanism through which the general framework in Gabaix and Maggiori (2014) is at work. Gabaix and Maggiori (2014) develop a model in which the exchange rate is determined by international capital flows and financially constrained intermediaries. I point out that the exporters induce capital flows with strong intraday patterns. Risk-averse financial intermediaries require compensation for absorbing the capital flows, which causes a specific pattern in exchange rate dynamics.

This paper is also related to the research on segmented markets and constrained arbitrageurs, such as Gromb and Vayanos (2002) and Gromb and Vayanos (2010). This paper identifies the exporters' net position as the demand-side shock that changes asset prices in different trading sessions. Unlike the cited papers, this paper focuses on the first order effect of market segmentation, and ignores further distortions such as the leverage and liquidity constraints.

In a general sense, the economic argument in this paper is similar to Grossman and Stiglitz (1980) and Grossman and Miller (1988). If mispricing is eliminated in the foreign exchange market, the financial intermediary cannot make profits to compensate for their fixed cost and risk. Then there will be no counterparty that trades with the exporters. Therefore under the current structure of the foreign exchange market, in which traders are segmented by time zones, mispricing and therefore return predictability are inevitable.

On the empirical side, I discover a novel trading strategy that has high expected returns and low volatility. The gains from this long-short strategy come from everyday difference between the distributions of exchange rate movements during US and EU business hours. I also find that its expected return is time-varying and predicted by the past exchange rate volatility. These observations support my explanation.

The empirical finding of Bjønnes, Rime, and Solheim (2005) supports my interpretation. Using a unique dataset from Swedish Krona market, they document that change in non-financial traders' net position lead to losses whereas change in financial traders' net position lead to profits. The coefficients are of similar magnitude. This relationship is consistent with the story that the hedgers offer price concession to the financial traders in order to offload their exchange rate risk.

A popular topic in recent finance literature is the carry trade return, achieved by taking a long position on currencies with high interest yield and a short position on currencies with low interest yield, usually dollar or yen. The return of the long-short strategy can be compared with the carry trade return in several dimensions. First, the long-short strategy requires intraday trading, whereas the carry trade portfolio is usually rebalanced quarterly. Second, the annualized sharpe ratio achieved by the carry trade is 0.4 (in Lustig and Verdelhan (2007)) to 0.6 (in my calculation), which is smaller than that of the long-short strategey, 0.8. Third, the expected return of long-short strategy is increasing in the volatility of the underlying exchange rate in the near past. This pattern for the carry trade return is not documented in the literature, and is rejected by my calculation[3]. Finally, Brunnermeier, Nagel, and Pedersen (2008) find that carry trade return is subject to the crash risk and therefore has negative skewness, but the return of the long-short strategy has positive skewness.

The rest of the paper is organized as follows. Section I presents the empirical characteristics of the long-short strategy. Section II formulates the model and examines its key predictions using the intraday exchange rate data. Section III exploits cross-country variation in the exchange rate dynamics and in invoicing activity to further support the economic argument in the paper. Section IV concludes with a short discussion.

I. Returns in Different Time Zones

A. Market Overview and Data Sources

The foreign exchange (FX) market is the largest financial market in the world. According to Wikipedia[4], the interbank market is the top-level, wholesale foreign exchange market where most currency transactions are channeled. A distinctive feature of this market is that it opens 24 hours in each weekday, since no matter what time it is, there are always some banks in business. During their business hours, banks constantly quote bid and ask prices based on anticipated currency movements and thereby make the market. Major banks like UBS, Barclays Capital, Deutsche Bank and Citigroup handle very large currency trading transactions often in billions of dollars. These transactions cause the primary movement of currency prices in the short term.

I use the Bloomberg BFIX database, which documents exchange rates in the interbank market every 30 minutes from 2007-03 to 2014-12. The rates are created by taking a short-term time-weighted average of the exchange rates leading up to and following the reported time spots. The database also contains bid and ask quotes from 2010, which enables me to estimate the transaction costs.

I use CRSP value-weighted, cum-dividend stock index as the stock market returns, from 2007-03 to 2014-12.

B. Return Divergence and Trading Strategy

For each trading day from 2007-03 to 2014-12, I calculate the exchange rate movement during US business hours (from 4 PM London time to 5 PM New York time) and EU business hours (from 8 AM to 4 PM at London time) respectively. Results are similar if I use alternative definitions of business hours.

[3]I use the portfolio approach documented in Lustig and Verdelhan (2007). I find no relationship between the 3-month return of carry trade portfolios and the realized volatility of daily exchange rate movements in the past 3 months.

[4]This paragraph is adapted from `http://en.wikipedia.org/wiki/Interbank_foreign_exchange_market`.

	Stock	US	EU	Long-Short
Annualized Mean	6.62%	6.12%	−5.90%	12.02%
Annualized SD	22.54%	4.81%	7.87%	9.02%
Annualized Sharpe Ratio	29.4%	127.3%	−74.9%	133.3%
Correlation with Stock	100%	27.4%	17.4%	−0.6%

Table I Returns of Different Assets. This table reports summary statistics of the daily returns of common stocks and different USD/EUR trading strategies, from 2007-03 to 2014-12. Column Stock reports the statistics of the stock index returns. Column US and EU report the US and EU business hour returns of USD/EUR respectively. The final column reports the returns of the long-short strategy. All returns are in log units, and transaction cost is not considered.

These returns are achieved by buying and selling currencies at daily frequency. The bid-ask spread is therefore an important transaction cost consideration for individual speculators who want to execute these strategies. The bid-ask spread is not a frictional cost, but simply transfer between market makers and other market participants. The dealers and other market makers may be able to execute these strategies with zero or even negative transaction cost. So I ignore transaction cost in this subsection to reflect the trading profits of these strategies when implemented by a market maker. The transaction cost will be discussed in Subsection D, where I use a shorter sample that contains bid and ask quotes to show that transaction cost does not offset the profit.

Table I compares the summary statistics of the returns of different trading strategies. Absent the transaction cost, the long-short strategy has high profit and low volatility. In addition, since the US and EU business hour returns have similar correlations with the US stock return, the long-short strategy has nearly 0 correlation with the US stock return. So the long-short strategy is a great market-neutral strategy. This observation also holds if I replace the US stock index by European stock indices.

The return of the long-short strategy has a positive skewness of 0.19 and an excess kurtosis of 1.99. This is in contrast with the carry trade profit, which has a highly negative skewness. Brunnermeier et al. (2008) discusses this point in detail.

Finally, the realized 5-day and 20-day volatilities of EUR/USD exhibit large variation in the time series, and they predict the return of the long-short strategy. I sort daily returns of the long-short strategy by the realized volatilities in the near past, and calculate the conditional returns. Table II shows that across the quintile groups, the more volatile the exchange rate was in the past few days, the higher the return and the volatility of the long-short strategy tend to be. The model developed in this paper produces equilibrium exchange rate dynamics consistent with this observation.

There are two natural questions to follow. Is this return divergence driven by discrete events? How does the transaction cost affect the profit? I will address them in the following subsections.

Historic 5-day Volatility					
Quintile	[0.06%,0.33%]	(0.33%,0.46%]	(0.46%,0.59%]	(0.59%,0.78%]	(0.78%,2.30%]
LS Mean Return	2.71 bps	5.09 bps	4.68 bps	6.16 bps	8.01 bps
LS Vol	0.42%	0.48%	0.50%	0.60%	0.76%
Test of Diff Mean	$t = 1.24$, P(Q1 and Q5 have the same mean return) = 11%.				
Historic 20-day Volatility					
Quintile	[0.18%,0.40%]	(0.40%,0.52%]	(0.52%,0.61%]	(0.61%,0.77%]	(0.77%,1.62%]
LS Mean Return	2.93 bps	4.22 bps	4.49 bps	6.14 bps	8.87 bps
LS Vol	0.34%	0.44%	0.52%	0.61%	0.82%
Test of Diff Mean	$t = 1.37$, P(Q1 and Q5 have the same mean return) = 8.6%.				

Table II The Return of Long-Short Strategy Conditional on Historic Volatility. The daily returns are grouped by quintiles of historic volatility. For day t, the historic n-day volatility is the standard deviation of the daily exchange rate movement of USD/EUR from day $(t-n)$ to day $(t-1)$. Row Quintile reports the range of historic volatility in each quintile group. Row LS Mean Return and Row LS Vol report the mean and the standard deviation of the long-short strategy's returns in each quintile group respectively. Row Test of Diff Mean reports the t-statistics and p-value of the test of difference in means between the returns in the first and in the last quintile group.

C. Macroeconomic Events

There are two ways in which this return divergence may emerge. It can be driven by a set of discrete events. When such an event hits the market, the return divergence between EU and US business hours widens; otherwise there is no difference in the distribution of business hour returns. Alternatively, the return divergence can build up day by day, as a result of a permanent difference in exchange rate dynamics between US and EU business hours. These two views imply different distributions of US and EU business hour returns.

The data favors the second view. The histograms of returns in different business hours are plotted in Figure 2. Both US and EU business hour returns have bell-shape distributions, and the EU business hour returns have slightly lower mean. We do not see heavy tails of extreme returns corresponding to the discrete events that widen the return divergence.

The finance literature documents a large effect of macroeconomic announcements on asset prices. For example, Moench and Lucca (2012) find a significant stock price drift prior to FOMC announcements. The nominal exchange rate model also focuses extensively on monetary policies since Frenkel (1976). I look at exchange rate movements around FOMC and ECB monetary announcement dates, as well as nonfarm payroll release dates. If some events are responsible for the return divergence, the events are likely to come around these announcement dates.

Figure 3 plots the average cumulative returns around FOMC announcements. If FOMC announcements indeed affect the return divergence, we should expect a sudden widening of return divergence around the announcement dates. And in the non-event dates, there should be no divergence in US and EU business hour returns. However, in the data the average US business hour returns are consistently higher than the average EU business hour returns. Price series around

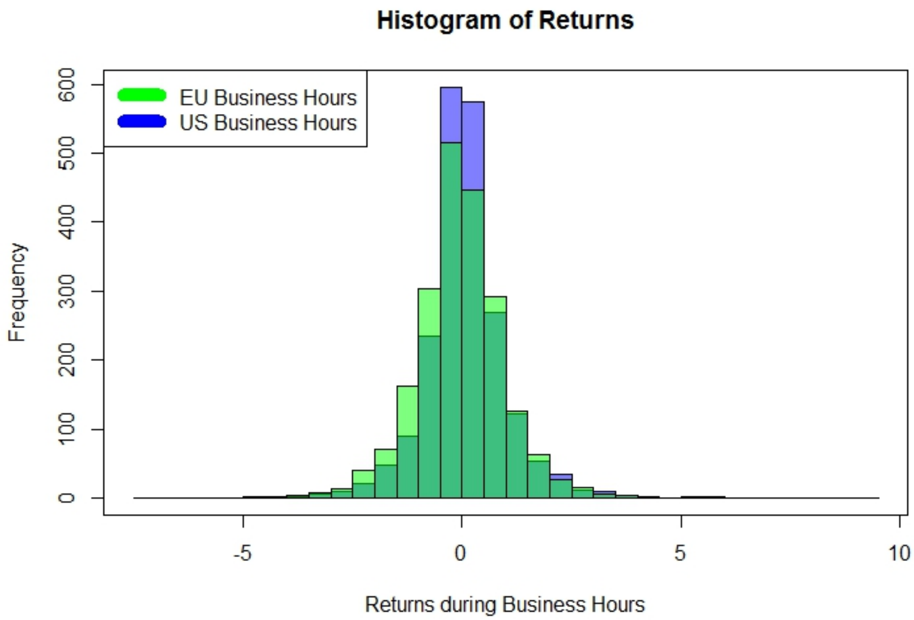

Figure 2. Histogram of Returns in Different Business Hours. The histograms of US and EU business hour returns of Euros against dollars are overlapped together. The returns are rescaled by their respective standard deviation to account for EU business hour returns' higher volatility.

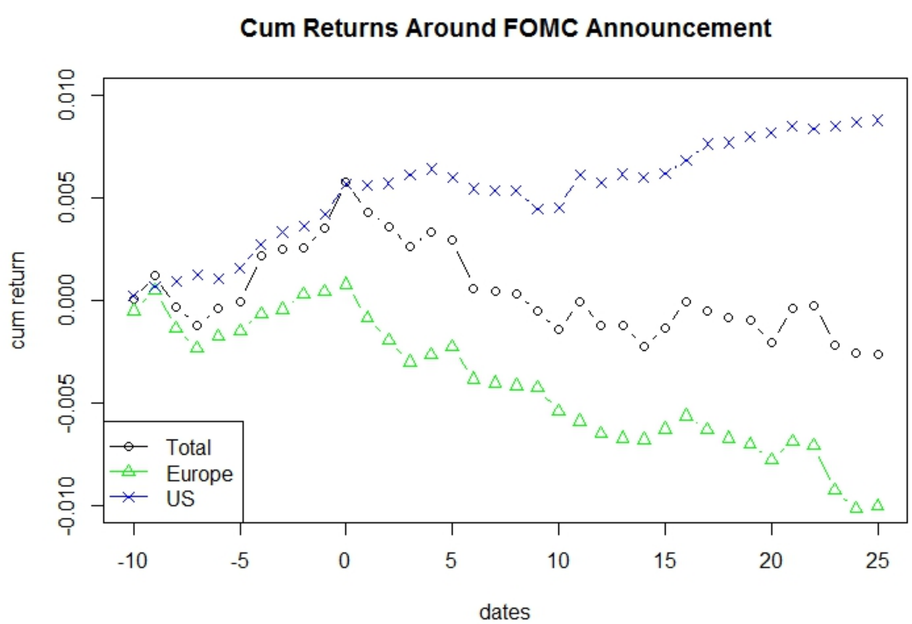

Figure 3. Average Cumulative Return around FOMC Announcements. The line in the middle plots the average cumulative exchange rate movements starting from 10 days before an FOMC announcements. The upper and lower lines plot the average cumulative US and EU business hour returns over the same set of dates.

	with Transaction Cost	no Transaction Cost	no Transaction Cost
Sample Period	2010-07 to 2014-12	2010-07 to 2014-12	2007-03 to 2014-12
Annualized Mean	6.60%	10.87%	12.02%
Annualized SD	8.31%	8.31%	9.02%
Annualized Sharpe Ratio	79%	131%	133%
Correlation with Stock	−14%	−14%	−0.6%

Table III Returns of Long-Short Strategy with Transaction Cost. This table reports the log-returns of the long-short strategy with and without transaction cost.

ECB monetary announcement dates and nonfarm payroll release dates show similar patterns. I found that the long-short strategy returns around these announcement dates are not statistically different from the returns in other dates. I conclude that the return divergence is unlikely to be related to macroeconomic events.

D. Transaction Costs

The Bloomberg BFIX database documents bid and ask quotes of exchange rates since 2010-07. In this smaller sample, the long-short strategy offers an annualized mean return of 6.60% and annualized sharpe ratio of 79% after transaction cost, as reported by Table III. Over the same period, without transaction cost the annualized mean return is 10.87% bps and the annualized sharpe ratio is 131%, both of which are very close to the statistics of the returns in the full sample.

On average the bid-ask spread of the post-2010 sample is about 1 basis point for the business hours considered. The long-short strategy enters a position and liquidates twice in a day, so the transaction cost is close to 2 bps per trade per day. Since the daily expected return is $12.02\%/252 = 4.8$ bps, this calculation also suggests that transaction cost offsets a little less than half of trading profit.

Still, the return of the long-short strategy after transaction cost has an annualized sharpe ratio of 79% and a negative correlation with the stock return. The sharpe ratio of the stock market return in the sample period is only 29%. It presents a puzzling anomaly in the foreign exchange market.

II. Model

A. Set-up

In this section I develop an equilibrium model in the spirit of the hedger-speculator story given at the beginning of the paper. The model is adapted from Osler (1995), which shows that the myopic speculators smooth the fundamental shocks and the exchange rate is a moving average of past shocks in equilibrium. The Osler (1995) model is applied to study numerous topics including the effect of foreign exchange intervention in Osler (1998); the connection between rational speculation and exchange rate volatility in Carlson and Osler (2000); the role of interest rate differential and

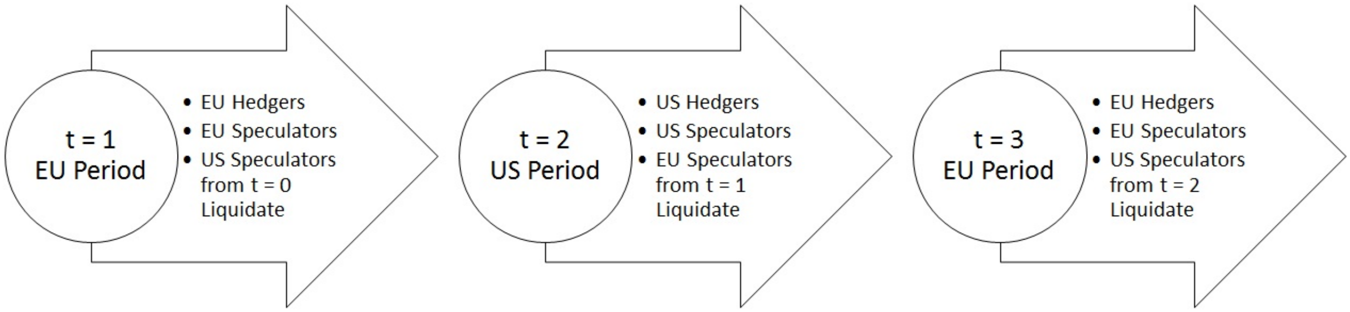

Figure 4. Timing of Events.

exchange rate in the short run dynamics in Carlson and Osler (2005). In a very similar spirit, the balance between hedgers and speculators is also the central issue in Blanchard et al. (2005) and Hau and Rey (2006).

I make two innovations. I match the vaguely specified "periods" to the actual trading sessions in the foreign exchange market. As the return divergence documented in the paper suggests, EU and US business hours should be regarded as separate periods. This allows the exchange rate dynamics to be different across EU and US business hours.

I also introduce the key friction in the hedger-speculator story. In my setting the US exporters on average sell Euros while the EU exporters on average sell dollars, and they have to do so in their separate business hours. The combination of heterogeneous currency supply and market segmentation leads to a new equilibrium whose characteristics match the empirical results.

The process plot in Figure 4 provides a reference for the timing of events. Time is discrete with an infinite horizon, starting at $t = -\infty$. Unlike traditional model that views each period as a day, a month or a year, the periods here are mapped to the different business hours: $t = \ldots, 1, 3, 5, \ldots$ correspond to EU business hours and $t = \ldots, 2, 4, 6, \ldots$ correspond to US business hours. They are called EU and US periods respectively. For simplicity, Asian business hours as well as the overlap between EU and US business hours are omitted. In the data I find that EUR/USD rate moves little during Asian business hours, and alternative definition of EU and US business hours produces similar results.

In each period the price is set so that the market clears, as if there were a Walrasian auctioneer. I ignore the process how the equilibrium is achieved.

There are two countries, US and EU. At time t, one Euros is exchanged for E_t US dollars in equilibrium. Denote $e_t = \log E_t$. The exchange rate E_t is determined at the start of time t, after which events that influence the next period's exchange rate occur.

There are two types of market participants: hedgers and speculators. The hedgers are exporters who trade foreign currency for hedging purposes. During EU periods, EU hedgers are working and US hedgers are sleeping, and vice versa. When hedgers are working at time t, they submit a demand schedule of foreign currencies that is affected by a shock to the fundamentals. The speculators, on the other hand, trade in all periods to maximize their expected utility.

A.1. Hedgers

The hedgers are the exporters who trade only to get rid of the foreign currencies earned overseas. The US hedgers' demand for Euros is specified as

$$F_t = C_t - Se_t + \epsilon_t, \text{ for US trading periods,} \tag{1}$$

where ϵ_t is the fundamental shock realized at the start of each period and $C_t > 0$ and $S > 0$ are scaling parameters. For trading period t, ϵ_t is a summary of unexpected shock realized at the previous period after trading occurs. For simplicity, ϵ_t is independent and has identical normal distribution with mean 0 and variance σ^2.

Modeling the nonfinancial traders' demand schedule as a function of asset price plus a random shock is a common practice in the finance literature, e.g. Goldstein and Yang (2014). It has a simple interpretation in my context. When the Euros is more expensive, US goods are cheaper and EU consumers buy more US goods. Suppose EU consumers' demand on US goods is elastic enough, which has empirical support in the international trade literature (e.g. Bahmani-Oskooee and Ratha (2004)), then the total Euros earned by US exporters increase. US hedgers sell more Euros, which leads to Eq. (1). The adjustment in price and quantity does not have to be fast, since the exchange rate is highly persistent and therefore the current exchange rate represents the average exchange rate in the past, over which period the price and quantity adjustment takes place.

In addition to the linear relationship between exchange rate and hedgers' demand schedule, there is a shock. The randomness comes from the fact that not all hedgers trade every day. In some days more hedgers sell foreign currencies and in some days fewer. In a broader sense, the randomness also includes macroeconomic events that affect the exchange rates. The assumption for this to be true is that the macroeconomic events are symmetrically distributed between US and EU business hours.

By a symmetric argument, EU hedgers' demand for Euros (which is the negative of demand for dollars divided by the exchange rate) in EU business hours is also

$$F_t = C_t - Se_t + \epsilon_t, \text{ for EU trading periods.}$$

Finally, the US exporters should on average sell Euros while the EU exporters should on average buy Euros. The market is segmented so that they cannot transact with each other to offset their orders – They have to exchange their position with the help of the speculators. The difference in US and EU hedgers' demand schedules is reflected in the level parameter C_t. I specify that

$$C_t = \begin{cases} C - M, & \text{for US trading periods;} \\ C + M, & \text{for EU trading periods.} \end{cases}$$

A.2. Speculators

Ideally I want to model the speculators who solve an investment-consumption problem over an infinite horizon. According to Blackwell's Theorem, the speculators with CARA utility have a unique value function. But if the interest rate is zero, which is the case for intraday traders in the foreign exchange markets, no known close form solution exists. In particular it can be shown that the value function is not of the form exp(k*wealth)*g(other state variables).

In order to have close form results, I assume the speculators are myopic, only caring about the trading profit realized in the next period. They represent the intraday and algorithmic traders in the foreign exchange market. These traders open positions at the beginning of each trading period, and liquidate all foreign assets at the end of the trading period to avoid overnight risk.

Formally, at period t, a new generation of speculators is born and they optimize a CARA utility on dollar profits realized at the beginning of period $t+1$. One such speculator maximizes

$$U_{t+1} = -\mathbb{E}_t[e^{\gamma B_t (E_{t+1}/E_t - 1)}], \tag{2}$$

where B_t is the amount of Euros the speculator chooses to hold. Take linear approximation and recall $e_t = \log E_t$, $E_{t+1}/E_t - 1 \approx e_{t+1} - e_t$. Since the exchange rate moves slowly, $E_{t+1}/E_t \approx 1$, and therefore the approximation is very accurate.

As will be confirmed below, I conjecture e_{t+1} is normally distributed condition on e_t. Under this conjecture, the problem is equivalent to maximizing

$$\mathbb{E}_t[B_t(e_{t+1} - e_t)] - \frac{\gamma}{2} Var_t(B_t e_{t+1}), \tag{3}$$

which has a simple solution

$$B_t = Q_t(\mathbb{E}_t[e_{t+1}] - e_t), \tag{4}$$

where $Q_t \stackrel{\text{def}}{=} (\gamma Var_t(e_{t+1}))^{-1}$. To emphasize, each speculator holds B_t Euros at time t, and liquidates immediately after the shock at time $t+1$.

A.3. Market Clearing

Summarizing the behavior of the hedgers and speculators, in each period the total demand for Euros is the sum of hedging demand and speculative demand, minus the liquidated position from the speculators born at the preceding period. Assume there are N speculators in each period, the market clearing condition implies

$$0 = \underbrace{C_t - Se_t + \epsilon_t}_{\text{Hedgers at } t} + \underbrace{NQ_t\left(\mathbb{E}_t[e_{t+1}] - e_t\right)}_{\text{Speculators Born at } t} - \underbrace{NQ_{t-1}\left(\mathbb{E}_{t-1}[e_t] - e_{t-1}\right)}_{\text{Speculators Born at } t-1}, \text{ for all } t. \tag{5}$$

For simplicity, I assume that the speculators in both US and EU periods optimize trading profits in terms of dollars. Relaxing this assumption is equivalent assuming the aggressiveness of speculators, Q_t, is different between EU and US periods, which does not change the main results.

A.4. Solution and Interpretation

Define the equilibrium to be a sequence of prices e_t under which the speculators make optimal trading decision and the market clears. Since the only randomness is the shocks $\{\epsilon_t\}$ and we want e_t to be stochastic, we focus on equilibrium in which e_t depends on ϵ_t. The existence of an equilibrium with such property is characterized in the following proposition.

PROPOSITION 1: *There is an equilibrium in which the exchange rate is a moving average process:*

$$e_t = \alpha_t + \sum_{i=0}^{\infty} \beta_i \epsilon_{t-i}, \tag{6}$$

with unique parameter values

$$\alpha_t = \frac{C}{S} - \frac{(-1)^t M}{S + 4NQ} \text{ and } \beta_i = \frac{1-\lambda}{S}\lambda^i, \text{ where } \lambda = \frac{NS}{\gamma\sigma^2} \text{ and } Q_t \equiv Q = \frac{1}{\gamma\beta_0^2\sigma^2}. \tag{7}$$

This $MA(\infty)$ process is equivalent to an $AR(1)$ process,

$$e_t = \alpha_t + \gamma_t \text{ where } \gamma_t = \lambda\gamma_{t-1} + \beta_0\epsilon_t \tag{8}$$

The proof is given in the Appendix. The solution indicates that ϵ_t affects all future periods but

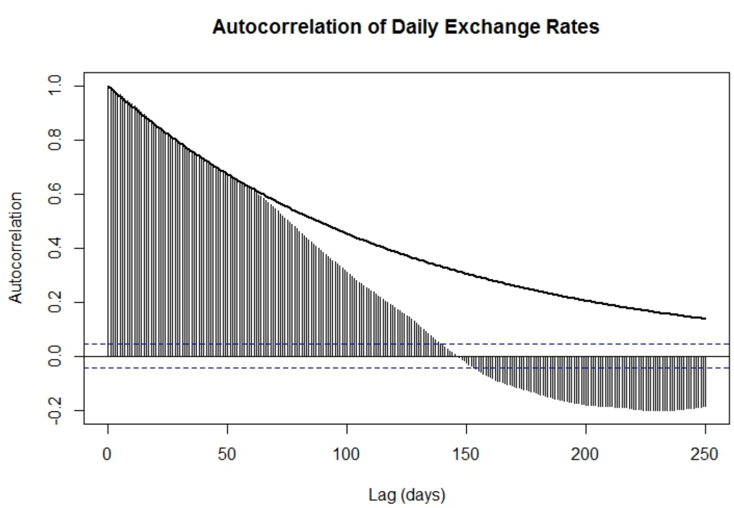

Figure 5. Autocorrelations of daily USD/EUR exchange rates. The vertical bars plot the autocorrelations up to a lag of 250 days of USD/EUR exchange rates, sampled at 4PM London time at each day. The curve is the autocorrelations of a fitted $AR(1)$ process whose parameter is estimated by the nonlinear least square method using the first 61 realized autocorrelations.

its impact diminishes as time passes. The moving average property with exponentially decaying weights is consistent with the data. Figure 5 plots the estimates of autocorrelations of daily USD/EUR exchange rates. For the first 60 days of lags, the estimated autocorrelations indeed decay at an exponential rate. There seems to be mean-reversion (i.e. negative autocorrelation) at a longer horizon, which is not modeled here since this paper focuses on the short-term dynamics.

Further, it is the speculators who perform the role of smoothing exchange rate changes. The exponential decay rate λ is increasing in the number of speculators N and decreasing in the perceived risk of speculation, which is determined by the risk aversion γ and fundamental volatility σ^2.

The hedgers are also crucial for the model. Were there only speculators, β_i is 1 for all i. In words, all shocks become permanent. The intuition is that the hedgers' demand schedule contributes a mean-reverting force to the exchange rate dynamics, without which the exchange rate follows a random walk. Rossi (2006) finds econometric evidence supporting the view that exchange rates do not follow a random walk.

B. *Return Divergence*

By Proposition 1, if $M > 0$ in both US and EU periods, then the Euros is expected to appreciate during US periods and to depreciate during EU periods. Formally, Eq. (7) implies

$$\Delta e_{t+1} \stackrel{\text{def}}{=} e_{t+1} - e_t = \frac{2M}{S + 4NQ} + \beta_0 \epsilon_{t+1} - \sum_{i=1}^{\infty} (1 - \lambda) \beta_i \epsilon_{t-i}, \text{ for US trading periods.} \tag{9}$$

Given $M > 0$, $\mathbb{E}[\Delta e_{t+1}] = 2M/(S + 4NQ) > 0$ for US trading periods. Similarly, $\mathbb{E}[\Delta e_{t+1}] = -2M/(S + 4NQ) < 0$ for EU trading periods. This pattern is summarized in the following observation.

OBSERVATION 1: *Under the assumption $M > 0$, the expected return divergence between consecutive US and EU business hours is*

$$R \stackrel{\text{def}}{=} \mathbb{E}[\Delta e_{t+1}] - \mathbb{E}[\Delta e_t] = \frac{4M}{S + 4NQ} > 0,$$

consistent with the return of long-short strategy observed in the data.

Moreover, since speculators' aggressiveness $Q = (\gamma \beta_0^2 \sigma^2)^{-1} = S^2((1 - \frac{NS}{\gamma \sigma^2})^2 \gamma \sigma^2)^{-1}$ is decreasing in the variance of fundamental shocks σ^2, we also have the following observation.

OBSERVATION 2: *The expected return divergence R is increasing in σ^2, consistent with the empirical observation that the return of long-short strategy tends to be higher when the historic volatility of exchange rate movement is high.*

This observation is consistent with the story at the beginning. Since the risk-averse speculators on average carry a positive amount of foreign currency into the next period, they demand a higher compensation if the volatility of exchange rate is higher.

C. Calibration

In this section I present a numerical example to make sure this model behaves well with reasonable parameter values. To estimate the parameter values, I simply use the method of moments since the number of parameters matches the number of interesting moment conditions. To begin with, notice out of the 6 primitive parameters $(C, S, M, N, \sigma^2, \gamma)$, two cannot be identified exactly:

- N and γ always appear together in the model in the form of N/γ. If we scale both the number of speculators N and their absolute risk aversion γ by any factor, the model is mathematically the same. This follows from the fact that in this setting CARA speculators submit orders proportional to $1/\gamma$. For convenience I take $\gamma = 1$.
- The market clearing equation still holds if C, S, M, N are scaled by the same factor. So I drop one more parameter by taking $N = 1$.

Then I use the following four moment conditions to solve for the remaining four parameters:

- The unconditional mean of Eq. (6) pins down the unconditional mean of exchange rates:

$$\mathbb{E}[e_t] = \frac{C}{S}. \tag{10}$$

- In the model the autocorrelation decays exponentially. To reduce noise, I match the autocorrelation with a lag of 60 days:

$$\frac{\sum_{i=0}^{\infty} \beta_i \beta_{i+120} \sigma^2}{\sum_{i=0}^{\infty} \beta_i^2 \sigma^2} \stackrel{\text{def}}{=} cor(\sum_{i=0}^{\infty} \beta_i \epsilon_{t-i}, \sum_{i=0}^{\infty} \beta_i \epsilon_{t+120-i}) = cor(e_t, e_{t+120}). \tag{11}$$

- A transformation of Eq. (6) pins down the expected return divergence between consecutive US and EU business hours:

$$\mathbb{E}[e_{t+1} - \lambda e_t] = \alpha_{t+1} - \lambda \alpha_t. \tag{12}$$

- The same transformation also pins down the variance of currency returns:

$$var(e_{t+1} - \lambda e_t) = \mathbb{E}[(e_{t+1} - \lambda e_t - \alpha_{t+1} + \lambda \alpha_t)^2] = \beta_0^2 \sigma^2. \tag{13}$$

Replacing all the expectations and variances with their empirical counterparts, I find a unique solution $C = 0.73, S = 0.53, \sigma^2 = 0.53, M = 0.17$. With these parameter values, the four moment conditions are matched exactly. In this system, the EUR/USD exchange rate has long run mean of 1.37 but the shocks are highly persistent with an autocorrelation factor $\lambda = 0.995961$. The return divergence between business hours observed in the data is the same as in the model, as well as the magnitude of the conditional variance of exchange rates $var_t(e_{t+1})$. Finally, the hedgers' demand schedules are

$$F_t = \begin{cases} 0.56 - 0.53e_t + \epsilon_t, & \text{for US trading periods;} \\ 0.90 - 0.53e_t + \epsilon_t, & \text{for EU trading periods.} \end{cases}$$

In particular the parameters S and C_t have the correct sign. For reasonable values of e_t and ϵ_t, the US exporters indeed sell Euros and the EU exporters sell dollars.

III. Long-Short Returns and Invoicing Practice

I document the return pattern of the long-short strategy and provide an explanation based on market segmentation and exporters' non-fundamental trading activity. In the two-country model, if the exporters from both countries receive foreign currencies, their asynchronous trading patterns induce temporary price deviation. If, on the other hand, exporters from both countries invoice their trades with the same currency, they do not need to trade across time zones. For example, if US-Japan trade is invoiced only in dollars, then US exporters and importers do not need to trade Japanese Yen, and Japanese exporters and importers can trade dollars on their own.

We can therefore exploit the cross-country variation in international trade invoicing practice and compare it with the variation in the long-short strategy returns of these countries' currencies. I plot the percentage of imports invoiced in home currency in Figure 6, in which the data is borrowed from four sources: Kamps (2006), Bekx (1998), Goldberg and Tille (2008) and the 2014 ECB publication "the international role of the euro". From the figure, almost all US imports are invoiced in dollars, half EU imports in Euros, 35% UK and Australia imports in their currencies and 25% Japanese imports in Yen.

This pattern coincides with the pattern of the long-short returns, presented in Figure 7. The bars for country X represents the return of the strategy that longs X's currency during US business hours and shorts X's currency during X's business hours. The US-EU pair is closer to our ideal in which exporters in both countries receive foreign currencies, and Euros indeed depreciate against dollars during US business hours and depreciate EU business hours. Less home currency is used in UK and Australia imports, and the long-short strategies based on British Pounds or Australian Dollars have smaller return.

The US-Japan pair is the farthest from our ideal because US exporters receive dollars. Then US exporters do not need to sell Yen, and Japanese exporters and importers can trade dollars *in the Japanese business hours.* The sign of long-short return for USD/JPY pair is negative, suggesting that the exporters' trading activity does not determine the intraday dynamics of USD/JPY, and some other forces are at work to induce the opposite pattern.

Although no causal link can be drawn from these observations, the pattern of invoicing practice is consistent with the implications of the model.

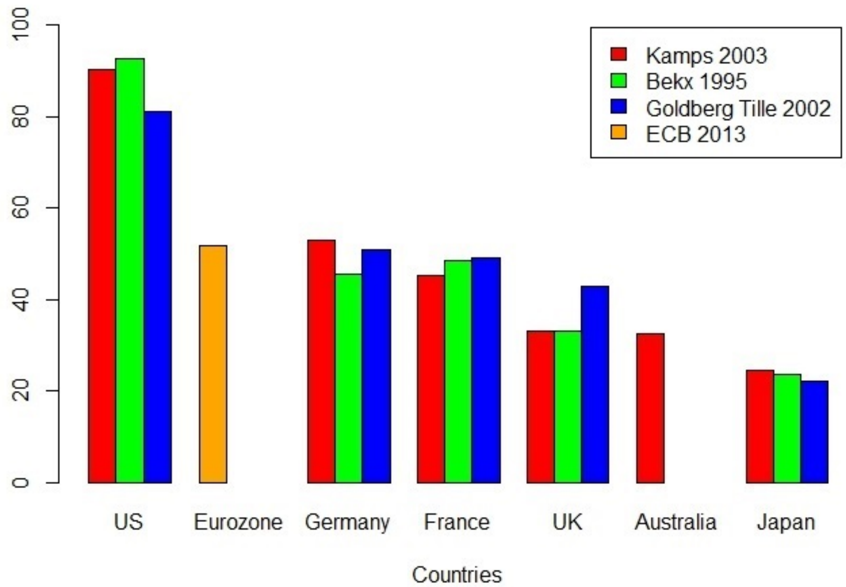

Figure 6. Percentage of imports invoiced in home currency. The bar plots in each country group represent the percentage of its imports invoiced in its home currency. There are multiple bars in each group because there are multiple data sources, indicated in the legend. The year in the parenthesis refers to the year in which the data is sampled.

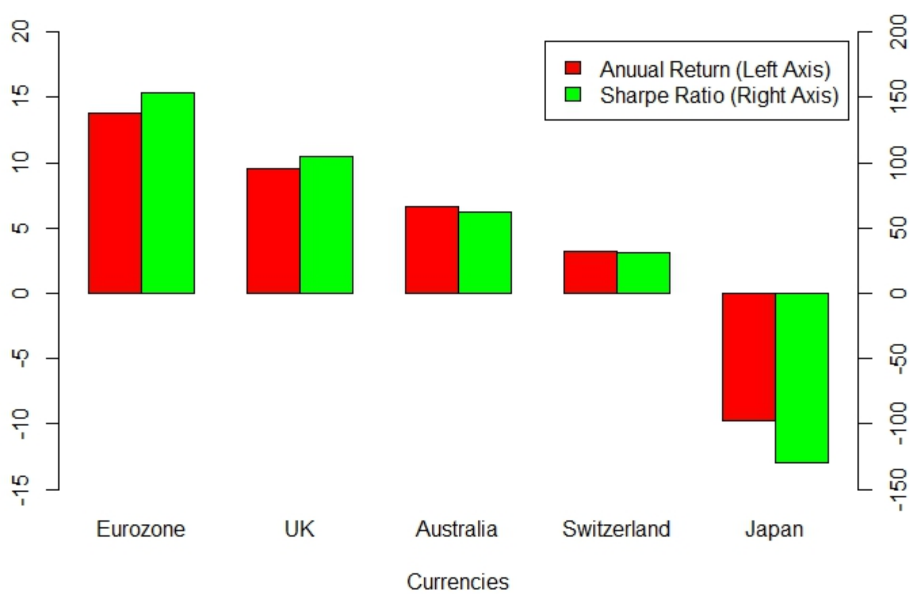

Figure 7. Returns of Long-Short Strategies. The bars for country X represents the annual return and Sharpe ratio of the strategy that longs X's currency during US business hours and shorts X's currency during X's business hours. The unit is percentage points and the transaction cost is ignored.

IV. Discussion

This paper documents the pattern that foreign currencies tend to appreciate during home business hours. Trading based on this principle produces large profits. I offer a story based on currency hedgers' demand patterns, which is internally consistent and matches several key characteristics in the data. Lack of data on what the hedgers actually do in each trading session, I cannot exclude all the other explanations. Instead, this paper only calls for attention to an asset pricing anomaly, and serves as a starting point to examine the mechanics behind it.

Interestingly, this empirical pattern is only found in EUR/USD, GBP/USD and CHF/USD pairs. It is puzzling to explain why European currencies are unique. In fact, Japanese Yen *appreciates* during its home business hours, and the gains during Japanese business hours account for the majority of Yen appreciation since 2007. Offering a complete explanation goes beyond the scope of this paper, but tentatively I suggest that money flowed to Yen denominated assets for safety and liquidity reasons is responsible. The inflow occurred during Japanese business hours since the aim is to purchase Yen assets traded during Japanese business hours. The inflow therefore causes the Japanese Yen to appreciate during home business hours.

Finally, this paper suggests that the financial intermediary earns a large risk premium in the foreign exchange market. It is a promising research area to examine the dealers' market power in such context. Will the introduction of new dealers compete away the profit each dealer makes? If so, what prevents outsiders from becoming foreign exchange dealers?

Appendix A. Proof of Proposition 1

Conjecture that $e_t = \alpha_t + \sum_{i=0}^{\infty} \beta_i \epsilon_{t-i}$ where the coefficients α_t and β_i are deterministic. Substitute e_t into the market clearing condition and collect coefficients of ϵ_s for each $s \leq t$. Since the equation holds for any value of ϵ_s, the coefficients must be 0. This result simplifies to the following difference equations

$$\beta_{i+1} - \beta_i(\frac{S + 2NQ}{NQ}) + \beta_{i-1} = 0; \tag{A1}$$

$$C - (-1)^t M = (S + 2NQ)\alpha_t - NQ\alpha_{t+1} - NQ\alpha_{t-1}, \tag{A2}$$

where $Q_t \equiv Q = \beta_0^2 \sigma^2$ because the conditional variance $var_t(e_{t+1})$ is a constant due to the conjecture.

The general solution to Eq. (A1) is $\beta_i = \xi_1 \lambda_1^i + \xi_2 \lambda_2^i$ where λ_j satisfies $\lambda_j^{i+1} - \lambda_j^i (S/(NQ) + 2) + \lambda_j^{i-1} = 0$, so

$$\lambda_{1,2} = \frac{S + 2NQ}{NQ} \pm \sqrt{(\frac{S + 2NQ}{NQ})^2 - 1}. \tag{A3}$$

Since the positive root $\lambda_2 > 1$, β_i explodes to infinity if $\xi_2 \neq 0$, contradicting to the common sense that the impact of past shocks is non-increasing. So $\xi_2 = 0$ and therefore $\beta_i = \xi_1 \lambda_1^i$. From the condition on the coefficients of ϵ_t, $\beta_0(S + NQ) = 1 + NQ\beta_1$, the explicit solution of β_t is obtained.

Conjecture $\alpha_t = C/S - (-1)^t x$, then Eq. (A2) implies $x = M/(S + 4NQ)$. Hence the solution of e_t is obtained.

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