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Revisiting the weak-form efficiency of the EUR/CHF exchange rate market: Evidence from episodes of different Swiss franc regimes

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HIGHLIGHTS

- We investigated the efficiency of the euro to Swiss franc exchange rate market via DMA/DFA method.
- The ultrahigh-frequency data and strict statistical tests are used to verify the weak-form efficiency hypothesis.
- Five episodes of different Swiss franc exchange rate policy regimes were studied.
- An extremely mild anti-persistence is found when the full sample is investigated.
- The majority of intraday Hurst indices follow a downward departure from 0.5.

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ABSTRACT

Based on ultrahigh-frequency returns, this paper comprehensively revisits the weak-form efficiency of the euro to Swiss franc (EUR/CHF) exchange rate market from 2002 to 2017, including the efficiency of several long periods and intraday efficiency. To this end, we employ Hurst index as the indicator of the degree of efficiency. The Jarque–Bera test demonstrates that the high-frequency logarithm return of EUR/CHF does not accord with a normal distribution. Further, a strict statistical test in the spirit of bootstrapping is performed to validate the statistical significance of Hurst indices of the EUR/CHF exchange rate returns. The results indicate that the EUR/CHF exchange rate market possesses an extremely mild anti-persistence when the full sample is investigated. Similarly, a weak anti-persistence is also found in five fixed sub-samples which can been roughly split into "free float" periods and "intervention" periods owing to the SNB's interventions. When it comes to the intraday efficiency tests on EUR/CHF exchange rate market, we find the majority of intraday Hurst indices follow a downward departure from 0.5, which roughly provides an evidence for intraday market inefficiency. Overall, at the level of long period returns, the Hurst values show an approach to 0.5, whereas most Hurst indices of intraday returns exhibit a relatively large deviation from 0.5. Besides, the intraday Hurst indices present that the announcement of lower bound can be approximatively regarded as a turning point of the market efficiency, which potentially indicates that the SNB's interventions might reduce the efficiency of the studied market.

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1. Introduction

It is a widely accepted notion that the foreign exchange (FX) markets play an extremely crucial role in the economic and financial systems [1]. The Swiss franc has a long reputation for being a safe haven currency and appreciates even though markets have been volatile and declining globally [2], which can be mainly attributed to the stabilized link with gold reserves regardless of the breakdown of Bretton Woods.[1] The Swiss franc presents a speedy upvaluation against most currencies (including euros) after the Global Financial Crisis in 2008/2009 [3]. Even the European sovereign debt crisis did not stop the euro against the Swiss franc depreciating. Since the launch in January 1, 1999, the euro has been the second most widely held international reserve currency [4], as well as a symbol of the strength of the European economy [5]. Naturally, the EUR/CHF exchange rate has become a pivotal exchange rate in the international monetary system.

As the Swiss economy severely suffered from a continuously weakening euro, on 6 September 2011 the Swiss National Bank (SNB) enforced a minimum exchange rate of 1.20 Swiss francs per one euro for an indefinite period of time, which can be achieved by purchasing foreign currency in unlimited quantities, see Fig. 1. The SNB held this policy until 15 January 2015. Overall, this exceptional and temporary measure protected the Swiss economy from serious harm. Then the Swiss franc's one-sided target zone during 2011–2015 became a focal point. Hui et al. [6] suggest that the EUR/CHF exchange rate follows a quasi-bounded process. Lera and Sornette [7] and Janssen and Studer [3] find that the target zone model outlined by Krugman [8] describes the EUR/CHF exchange rate well during this particular period. Further, several scholars have investigated the credibility of the exchange rate limit from option-price or option-theoretic perspectives [9–11]. For instance, Hanke et al. [9] use a compound option pricing approach to back out the latent exchange rate that would prevail in the absence of the exchange rate limit. Additionally, Streit [12] analyzes the effects of the enforcement of the Swiss currency floor on firm-level risk exposures for a sample of 147 Swiss non-financial firms.

In addition, the Efficient Markets Hypothesis (EMH) has constituted an enduring area of financial research since its introduction in 1960s. Fama [13,14] classifies market efficiency into three categories, namely, Weak Form Efficiency, Semi-Strong Form Efficiency and Strong Form Efficiency. There exist extensive literatures devoting to the study of the weak-form EMH which asserts that market prices reflect all historical price information [15–24]. More specially, considerable studies have been conducted to examine weak-form EMH in the context of asset return predictability based on past returns [20,21,25–27]. Hence, the unpredictability or randomness of asset returns can generally be linked to the weak-form efficiency of financial markets. Correspondingly, if asset returns are found to have predictive power, investors may be able to take advantage of these predictabilities, which in turn would be a violation of the EMH. In contrast, Lo [28,29] proposes a new version of the EMH derived from evolutionary principles, namely Adaptive Markets Hypothesis (AMH), under which the EMH and market inefficiency can co-exist in an intellectually consistent manner. What is more, based on the Fractal Brownian Motion (FBM), Mandelbrot [30,31] and Peters [32] support that the Fractal Market Hypothesis (FMH) can be a viable alternative to the EMH.

Despite extensive empirical investigation, conclusive evidence of the efficiency of FX markets remains elusive [33,34]. Such earlier studies as [35–37] show that real exchange rates should, or do, follow random walks. Then Hakkio [38] argues that empirical findings of random walks for real exchange rates may be caused by the low power of tests for the random walk hypothesis. While Huizinga [39] and Grilli and Kaminsky [40] find evidence against the random walk hypothesis. More recently, Neely et al. [41] unveil that the regularities of several FX markets are consistent with the AMH rather than the EMH. Likewise, the evidence from major currency markets indicates that predictability and profitability of foreign exchange returns change with changing market conditions, supporting the tenets of the AMH [41,42]. Further, Chang [43] conducts a reexamination of the random walk hypothesis for the Canadian dollar, French franc, Deutsche mark, Japanese yen and British pound, which provides evidence rejecting the random walk hypothesis for the Japanese yen over the entire sample, while the results for the other four currencies are inconclusive. Katusiime et al. [34] find that the Ugandan foreign exchange market is primarily characterized by weak form inefficiency and the time variation in market efficiency is consistent with the AMH [28]. In contrast, Chiang et al. [44] reexamine the validity of the weak form EMH for FX markets in four floating-rate markets in neighboring Asian economies, then conclude that the FX markets of Japan, South Korea and the Philippines are weak form efficient, while the FX market of Taiwan is relatively inefficient. Jeon and Seo [45] study whether the Asian financial crisis in the second half of 1997 affected the FX market efficiency in four Asian countries (Thailand, Indonesia, Malaysia and Korea). Their result is mostly consistent with the across-country EMH in the Asian FX markets during the whole sample period except the short period immediately after the July 1997 crisis. Azad [46] empirically tests the random walk and efficiency hypothesis for 12 Asia-Pacific FX markets, suggesting that the majority of markets are efficient with the daily data but not with the weekly data. Especially, based on the order flows at tick-by-tick transaction level, Kitamura [47] proposes simple market efficiency measures in FX markets, indicating high liquidity enhances market efficiency in the EUR/USD and USD/JPY markets.

Indeed, the majority of studies on the EMH examine FX rates against the US dollar. To the best of our knowledge, there exist several studies that evaluate the EMH for euro-based nominal exchange rates. Concretely, with the traditional variance ratio test [15,48] and the variance ratio tests based on ranks and signs [49], Belaire-Franch and Opong [50] investigate the behavior of daily euro exchange rate returns for 10 countries and observe a negative dependence in most of the exchange rate return series examined. Also, their results present a weak rejection of weak-form EMH for the

[1] Proceedings and Documents of the United Nations Monetary and Financial Conference, Bretton Woods, New Hampshire, July 1–22, 1944.

euro/Swiss franc exchange rate. Charles and Darné [4] employed new variance ratio tests to evaluate the random walk behavior of eleven major euro exchange rates over the period from January 4, 1999, to May 30, 2008, using daily and weekly data. They suggest that euro-based exchange rates for the major trading countries (Australia, Canada, Japan, UK, US, New Zealand, Korea and Switzerland) follow the random walk hypothesis at both data frequencies. Similarly, Belaire-Franch and Opong [51] utilize variance ratio tests based on the subsampling approach to test the behavior of euro-based exchange rates markets. They show mixed results that the null hypothesis of random walk can be rejected for Canada, New Zealand, Singapore, Sweden and Switzerland while Japanese yen, US dollar and British pound follow a random walk. Thereafter, Chortareas et al. [52] adopt Generalized Andrews–Ploberger tests to examine the random walk behavior of 17 OECD countries' euro exchange rates at daily frequencies, which indicated a random walk for the euro's exchange rate against most of the major currencies (including Swiss franc). Comprehensively, Cheung et al. [53] examine the serial uncorrelatedness behavior of 82 foreign currencies against the euro using three newly developed tests, which shows that most euro-based exchange rate markets are weak-form efficient. In particular, based on wavelet multiresolution analysis together with Hurst index, Karuppiah and Los [54] uncovered that almost all investigated high-frequency FX rates show antipersistent pricing behavior.

Summarily, alternative testing methods, different data periods, and dissimilar frequencies of data [44,46] have contributed to the controversial and mixed results in the literature on the EMH. For the variety of methods, there exist the unit root tests [35,36,39,55], the autocorrelation test [21], traditional variance ratio test [15,48], non-parametric sign and rank-based variance ratio test [49], the multiple variance ratio test [56], the Generalized Andrews–Ploberger test [52], the approximate entropy(ApEn) method [57], the methods related to Hurst exponent [54,58], to list a few. In particular, as mentioned by Azad [46], the high-frequency data are better estimates of the market efficiency of developed markets, where the volume of trading is very high and the markets are very competitive. Hence, the distinction of the results across the methodologies and the data frequencies is exceedingly significant.

Inspired by the SNB's market interventions and controversial conclusions of weak-form EMH on EUR/CHF exchange rate market, this paper aims to revisit the effect of the monetary policy shocks on market efficiency of EUR/CHF exchange rate. Based on the two high-performance nonparametric approaches [26,59,60], namely detrending moving average analysis (DMA) [61] and detrended fluctuation analysis (DFA) [62], we test the random walk hypothesis by calculating the Hurst index H of both long term and intraday EUR/CHF return series [63], together with the adoption of bootstrapping-based statistical tests and tick-by-tick data. Explanatorily, a time series is uncorrelated if its Hurst index $H = 0.5$, antipersistent if $H < 0.5$, or persistent if $H > 0.5$ [64]. The Hurst index significantly differing from 0.5 implies that the market is not efficient.

Overall, our contribution to this literature will be the presentation of persistence or anti-persistence property of EUR/CHF exchange rate market from episodes of different Swiss franc regimes, using a long-memory methodology for the weak-form EMH test. The rest of this paper is organized as follows. Section 2 depicts the data sets and presents the summary statistics. Section 3 explains the methodology. Section 4 reports the empirical results, and Section 5 concludes with a review of the main findings.

2. Data description

2.1. Data sets

Our analysis is based on the tick-by-tick quote data of EUR/CHF exchange rate from January 1, 2002 to August 31, 2017, with time stamps accurate to 1 s. Note that the FX market is a continuous global market, providing participants with 24-hour market access. Following Karuppiah and Los [54] and Piccotti [65], we use the mid-quotes as the exchange rate price series in order to have a cleaner estimate of the representative exchange rates. Fig. 1 (A) plots the evolution of the ultrahigh frequency prices of EUR/CHF exchange rate. Furthermore, an upward movement in the exchange rate series indicates depreciation of the Swiss franc, while a downward movement indicates appreciation.

Generally, central banks tend to adjust interest rates or trade in assets of a given currency to achieve a targeted exchange rate, which often fail due to market pressure. Following Janssen and Studer [3], five episodes of different monetary policy regimes were distinguished according to the SNB's official announcement in the Quarterly Bulletins.[2] In total, two "free float" periods were identified. The first regime stops on 12 March 2009, and the second regime last from 17 June 2010 to 6 September 2011. During these two regimes, the SNB did not announce any exchange rate target and its foreign currency reserves remained broadly unchanged. In contrast, two ordinary "intervention" periods were identified according to the SNB's prevention of Swiss franc from appreciating, which were between 12 March 2009 and 17 June 2010, and since 15 January 2015. More remarkably, these two intervention periods are not shaped by an explicitly announced exchange rate target, which significantly distinguishes them from the unique "lower bound" period during 2011–2015. Correspondingly, the four vertical lines in Fig. 1 separate five episodes of different Swiss franc exchange rate policy regimes

2 https://www.snb.ch/en/iabout/pub/oecpub/id/pub_oecpub_quartbul.

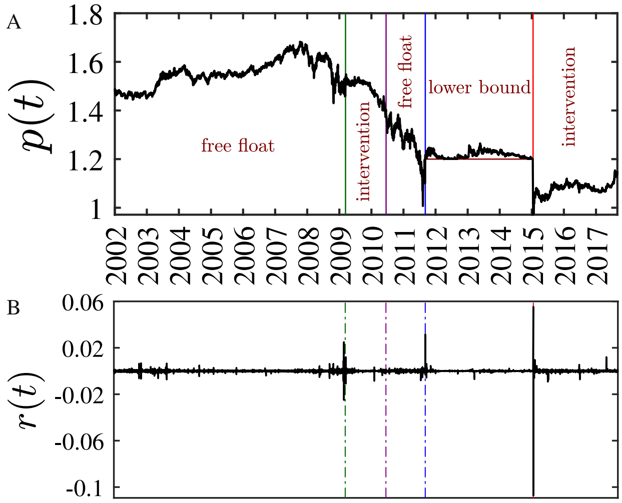

Fig. 1. (A) Evolution of the EUR/CHF exchange rate covering the period from January 1, 2002 to August 31, 2017 in tick-by-tick level. The horizontal line marks the period between September 6, 2011 and January 15, 2015, while the SNB officially announced its decision to enforce a minimum of 1.20 Swiss francs per euro by purchasing euros and selling Swiss francs in unlimited amounts if necessary. The four vertical lines mark separate five episodes of different Swiss franc exchange rate policy regimes. (B) Evolution of the logarithmic returns of EUR/CHF exchange rate in tick-by-tick level.

Table 1
Summary statistics for logarithmic returns of the EUR/CHF exchange rate.

Period	Length	Mean	SD	Min	Max	Skewness	Kurtosis	h_{ad}	p_{ad}	h_{jb}	p_{jb}
Whole	111157717	−0.0000000023	0.0000448	−0.107304080	0.055356455	−151.12	405026.0	1	0.0000	1	0.0000
Sub 1	33112483	0.0000000000	0.0000655	−0.025018931	0.024992115	−0.01	1365.5	1	0.0000	1	0.0000
Sub 2	17468164	−0.0000000035	0.0000380	−0.010925949	0.012055852	−1.21	1534.0	1	0.0000	1	0.0000
Sub 3	16588291	−0.0000000101	0.0000251	−0.008127084	0.012982027	8.34	6760.7	1	0.0000	1	0.0000
Sub 4	22811783	0.0000000009	0.0000175	−0.007064625	0.031608665	257.76	471078.3	1	0.0000	1	0.0000
Sub 5	21176996	−0.0000000023	0.0000425	−0.107304080	0.055356455	−947.75	2592037.5	1	0.0000	1	0.0000

2.2. Distributional statistics

The logarithmic return of the EUR/CHF exchange rate is defined as follows:

$$r(t) = \ln p(t) - \ln p(t-1), \tag{1}$$

where $p(t)$ represents the price of EUR/CHF exchange rate at time t. Fig. 1 (B) illustrates the evolution of ultrahigh frequency returns of EUR/CHF. Note that the four vertical dashed lines in Fig. 1 (B) correspond to the five episodes of Swiss franc regimes, which is similar with the solid lines in Fig. 1 (A). Explanatorily, the five different Swiss franc regimes are denoted as sub-sample 1, sub-sample 2, sub-sample 3, sub-sample 4 and sub-sample 5 based on their chronological orders (abbreviated as Sub 1, Sub 2, Sub 3, Sub 4 and Sub 5), respectively. Obviously, one can observe that there exist large fluctuations of returns around the four vertical dashed lines. In sharp contrast to this, the rest returns present a gentle fluctuation. More specially, the fluctuating behavior of the returns almost keeps an approaching to 0 during the unique "lower bound" period from 6 September 2011 to 15 January 2015, which can be validated in Fig. 2 (E).

Intuitively, Fig. 2 suggests that whole sample and five sub-samples of EUR/CHF exchange rate returns do not accord with normal distribution, characterizing with a leptokurtic distribution. Especially, Fig. 2 (D) is distinguished from other plots with the exceedingly low frequency for the returns around 0. Table 1 reports the descriptive statistics for the full sample and five sub-sample periods of EUR/CHF exchange rate returns and finds that all the mean returns are approaching to 0. Meanwhile, the length of full sample returns is 111157717 while the length of five sub-samples fluctuate within a wide range, from 16588291 to 33112483 (Sub 1 has the largest length, while Sub 3 has the smallest length). Table 1 presents the asymmetry between the maximum return (Max) and the minimum return (Min). Interestingly, all the standard deviation of returns is less than 0.0001. Furthermore, all samples are negatively skewed except for sub-sample 3 and 4, which are positively skewed. As expected, the Kurtosis in Table 1 shows that the returns are highly leptokurtic, indicating a peaked distribution. The Jarque–Bera statistic is a joint test of symmetry and mesokurtosis where the null hypothesis is normality. Clearly each sample period rejects the null hypothesis at 1%, confirming the idea that each sample period returns are not normally distributed. Similarly, the Anderson–Darling test provides further evidence that the EUR/CHF exchange rate returns are not normally distributed, which can be attributed to intertemporal dependence amongst the serial momentums [44].

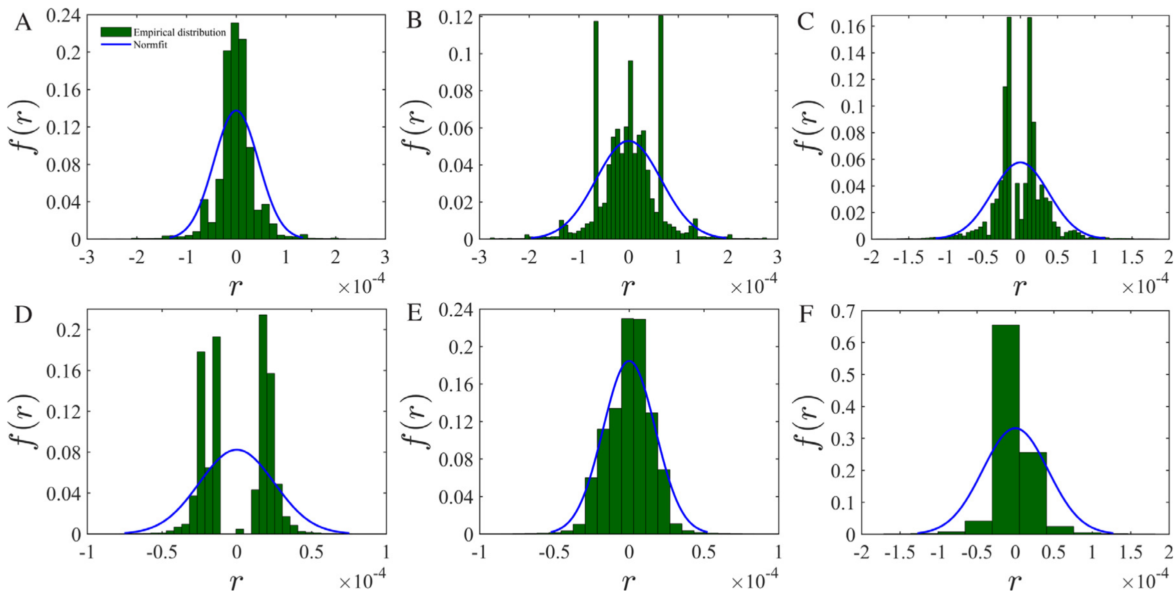

Fig. 2. Empirical distribution of ultrahigh frequency returns of EUR/CHF exchange rate. (A) corresponds to the full sample. (B-F) illustrate five different Swiss franc regimes, respectively. The blue line is a normal distribution fit.

3. Methodology

As mentioned, we adopt the DMA and DFA methods to determine the Hurst index of EUR/CHF exchange rate returns, which are two of the most effective and extensively used methods for the estimation of Hurst exponent [59] in nonstationary time series. For a brief recall, the DFA method was first introduced by Peng et al. [62] to detect the long-range correlation in coding and noncoding DNA nucleotide sequences. The properties of DFA have been thoroughly studied [66–68]. The DMA analysis is based on the moving average technique, which was first invented by Vandewalle and Ausloos [69] then further developed by Alessio et al. [61] via considering the residuals between the original signal and its moving average function. The DMA method has been widely applied to the long range dependence analysis of real-world time series [70,71] and synthetic signals [72,73]. Further numerical experiments suggest that the DMA method and the DFA method perform comparably with trivially different priorities while applied to different signals [59,72,74].

The DMA and DFA algorithms are briefly described as below, which share the similar framework [26,59]. For a given EUR/CHF return time series $\{r_i | i = 1, 2, \ldots, N\}$, we construct the cumulative summation series y_i as follows,

$$y_i = \sum_{j=1}^{i} (r_j - \langle r \rangle), \qquad i = 1, 2, \ldots, N. \tag{2}$$

where $\langle r \rangle$ is the sample mean of the r_i series. The series y_i is covered by N_s disjoint boxes with the same size s, where $N_s = \lfloor N/s - 1 \rfloor$. In each box, the local trend function $\widetilde{y}_i$ of the sub-series is determined. The residuals are calculated by

$$\epsilon(i) = y_i - \widetilde{y}_i. \tag{3}$$

The main difference between the DFA and DMA procedures is the determination of $\widetilde{y}_i$, which depends on the box size s. The local trend $\widetilde{y}_i$ could be polynomials, which recovers the DFA method [62]. When it comes to the DMA approach, one calculates the moving average function $\widetilde{y}_i$ over s data points [73],

$$\widetilde{y}_i(s) = \frac{1}{s} \sum_{k=-\lfloor (s-1)\theta \rfloor}^{\lceil (s-1)(1-\theta) \rceil} y_{i-k}, \tag{4}$$

where θ is the position parameter with the value varying in the range [0, 1]. Specially, the cases $\theta = 0$, $\theta = 0.5$ and $\theta = 1$ respectively correspond to the backward detrending moving average (BDMA) method, the centered detrending moving average (CDMA) method and the forward detrending moving average (FDMA) method. The local fluctuation function $F_v(s)$ in the vth box is defined as the root-mean-square of the residuals:

$$[F_v(s)]^2 = \frac{1}{s} \sum_{i=(v-1)s+1}^{vs} [\epsilon(i)]^2 \,. \tag{5}$$

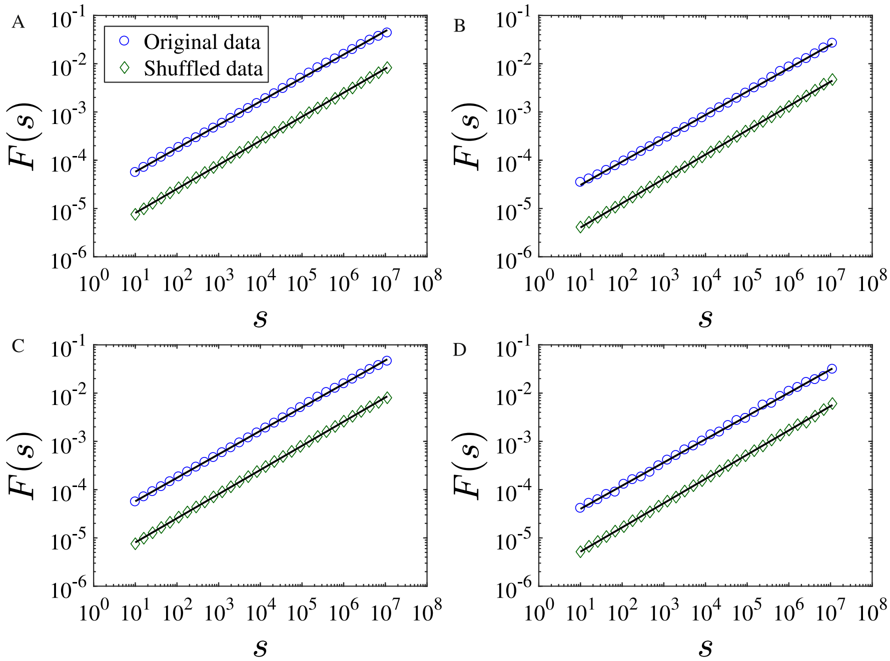

Fig. 3. Plots of the fluctuation function $F(s)$ with respect to the box size s for the whole sample and its shuffled series. (A) BDMA. (B) CDMA. (C) FDMA. (D) DFA.

The overall fluctuation function is calculated as follows:

$$F(s) = \left\{ \frac{1}{N_s} \sum_{v=1}^{N_s} F_v^2(s) \right\}^{\frac{1}{2}}, \tag{6}$$

Varying the values of box size s, one could determine the power law relationship between the fluctuation function $F(s)$ and the box size s:

$$F(s) \sim s^H, \tag{7}$$

where H can be roughly viewed as the Hurst exponent (Precisely, H signifies the DMA or DFA scaling exponent). Complementally, the power law scaling behaviors are ubiquitous in many systems [75,76]. If H is insignificantly different from 0.5, the return series r is uncorrelated. If H is significantly greater than 0.5, the EUR/CHF return series r is positively correlated. If H is significantly smaller than 0.5, the return series r is negatively correlated. Therefore $H \neq 0.5$ indicates long range dependence.

4. Results

This section presents analysis results for the memory behaviors in the EUR/CHF exchange rate returns via DMA and DFA approaches. Concretely, the investigated time series includes the whole sample, five sub-samples, and intraday samples. This study further carries out bootstrapping-based statistical tests to access whether EUR/CHF return series under investigation possesses long-term correlations.

4.1. The whole sample

To have an overall cognition of the long-term memory in the EUR/CHF exchange rate, we analyze the whole sample with DMA and DFA approaches. Fig. 3 illustrates the fluctuation function $F(s)$ with respect to the segment size s for the entire sample of EUR/CHF return time series. It is evident that these curves exhibit very nice power-law scaling behaviors between the fluctuation function $F(s)$ and the box size s in each panel and the solid lines are the best power-law fits to the data points in corresponding scaling ranges, which gives the exponents $H = 0.4858 \pm 0.0016$ for DMA with $\theta = 0$, $H = 0.4839 \pm 0.0019$ for DMA with $\theta = 0.5$, $H = 0.4865 \pm 0.0013$ for DMA with $\theta = 1$, and $H = 0.4811 \pm 0.0027$ for DFA, respectively. The Hurst value for the full sample shows an approaching to 0.48 regardless of the methods, indicating a weak anti-persistence.

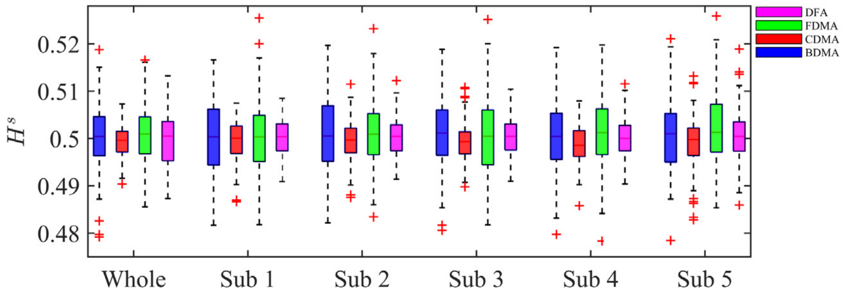

Fig. 4. Boxplot of the estimated exponent H^s of 152 shuffled series for the four approaches.

Table 2
Estimated Hurst exponents of the whole sample and the five sub-samples and the results of bootstrapping tests.

		Whole	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5
BDMA	H	0.4858 ± 0.0016	0.4679 ± 0.0028	0.4507 ± 0.0022	0.5083 ± 0.0020	0.4498 ± 0.0023	0.4466 ± 0.0022
	$\langle H^s \rangle$	0.5000	0.5002	0.5007	0.5008	0.5002	0.5005
	p	**0.0329***	**0.0000****	**0.0000****	0.3421	**0.0000****	**0.0000****
CDMA	H	0.4839 ± 0.0019	0.4432 ± 0.0050	0.4363 ± 0.0038	0.5108 ± 0.0030	0.4587 ± 0.0032	0.4417 ± 0.0033
	$\langle H^s \rangle$	0.4998	0.4997	0.4995	0.4995	0.4994	0.4996
	p	**0.0000****	**0.0000****	**0.0000****	**0.0000****	**0.0000****	**0.0000****
FDMA	H	0.4865 ± 0.0013	0.4684 ± 0.0030	0.4530 ± 0.0034	0.5053 ± 0.0025	0.4518 ± 0.0021	0.4401 ± 0.0013
	$\langle H^s \rangle$	0.5006	0.5002	0.5009	0.5006	0.5010	0.5013
	p	**0.0263***	**0.0000****	**0.0000****	0.5987	**0.0000****	**0.0000****
DFA	H	0.4811 ± 0.0027	0.4431 ± 0.0056	0.4506 ± 0.0049	0.5106 ± 0.0036	0.4584 ± 0.0038	0.4413 ± 0.0028
	$\langle H^s \rangle$	0.4999	0.5002	0.5002	0.5000	0.5001	0.5004
	p	**0.0000****	**0.0000****	**0.0000****	**0.0000****	**0.0000****	**0.0000****

*Denote the significance at 5% levels, respectively.
**Denote the significance at 1% levels, respectively.

To verify whether the original samples present the same memory behaviors as the shuffled series, we also conduct the same analysis on the shuffled series, which is obtained by reshuffling the original samples to remove possible memory behaviors. The illustration for a randomly chosen realization of the shuffled time series is plotted in Fig. 3 as well. Meanwhile, the Hurst exponents of the shuffled series show an extreme approaching to 0.5, providing an impression that the return series of the EUR/CHF exchange rate may exhibit different memory features from its shuffled series.

Emphatically, the deviation of Hurst index from 0.5 does not necessarily imply that the EUR/CHF exchange rate market is inefficient. To distinguish the memory behaviors of original samples and shuffled series strictly, we carry out a statistical test in the spirit of bootstrapping [26]. We define the Hurst index H as the statistic. Then we reshuffle the original samples for 152 times and estimate the Hurst exponent H^s for each shuffled series in order to capture the distribution of the statistic. The null hypothesis is that the original series exhibits the same memory behavior as the shuffled series, *i.e.*, $H = \langle H^s \rangle$, where $\langle H^s \rangle$ is the average Hurst exponent of all shuffled series. Fig. 4 illustrates the boxplots of H^s of the shuffled series for the four approaches, in which the Hurst indices are close to 0.5. In addition, the average values $\langle H^s \rangle$ are extremely close to 0.5, which are reported in Table 2. Intriguingly, observing Fig. 4 and Table 2, it is not difficult to find that

$$H^{\mathrm{BDMA}} \approx H^{\mathrm{FDMA}} > H^{\mathrm{CDMA}} \approx H^{\mathrm{DFA}}. \tag{8}$$

Following Jiang et al. [26], we apply a two-tailed p-value to quantify the difference in the long memory correlation of the original series and the shuffled series:

$$p = \mathrm{Prob}\left(|H^s - \langle H^s \rangle| > |H - \langle H^s \rangle|\right). \tag{9}$$

The p-value for the four methods is presented in Table 2. The results indicate that the null hypothesis can be rejected at the significance level of 5%, which offers the essential evidence supporting anti-persistence in return series of the EUR/CHF exchange rate. Nevertheless, for the BDMA and FDMA approaches, the null hypothesis cannot be rejected at the significance level of 1%. Explanatorily, Shao et al. [59] found that CDMA and DFA methods are the best and exhibit comparable performances. Hence, one can conclude that the EUR/CHF exchange rate market shows slight inefficiency when the whole sample is taken into consideration.

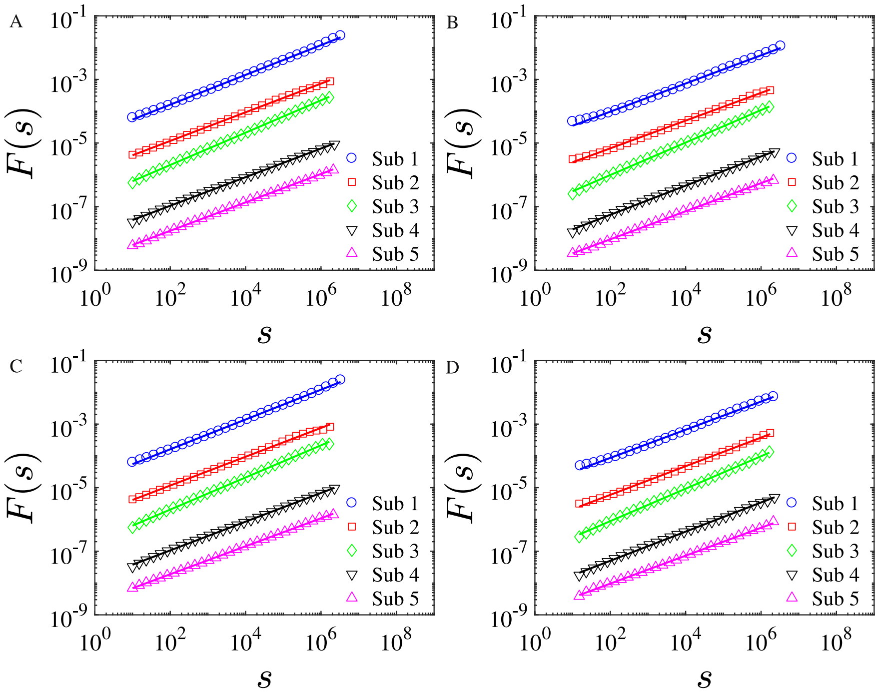

Fig. 5. Plots of the fluctuation function $F(s)$ with respect to the box size s for the five sub-samples and their shuffled series. (A) DMA with $\theta = 0$. (B) DMA with $\theta = 0.5$. (C) DMA with $\theta = 1$. (D) DFA.

4.2. Several sub-samples

As mentioned in Fig. 1 (A), several monetary policy regimes can be identified and related to different economic or geopolitical developments when recalling the evolution of the EUR/CHF exchange rate covering the period from January 1, 2002 to August 31, 2017. To identify the impacts of the SNB's officially announced policy stance on the memory behaviors in the EUR/CHF exchange rate, the DMA and DFA approaches are further employed to five sub-samples.

The five regimes are depicted in Section 2. Each sub-sample is analyzed with the DMA and DFA approaches as well as the whole sample. Analogously, Fig. 5 depicts excellent power-law dependence of the fluctuation functions $F(s)$ with the scale s for the five sub-samples, which covers more than four orders of magnitude. The Hurst exponents of the five sub-samples are reported in Table 2, in which the anti-persistence is revealed for almost every sub-samples except Sub 3. A supremely weak persistence is uncovered in free float period sub 3, which may be caused by regular financial turbulence (such as the European sovereign debt crisis). In contrast, the Hurst index of Sub 1 presents a downward departure from 0.5 although Sub 1 is also identified as a "free float" period, which can be attributed to an initial lack of credibility of the euro zone (the euro was launched in 1999) and several significant economic, financial and geopolitical events (such as the 2008 global financial crisis). In addition, the SNB's policy interventions of Sub 2, Sub 4 and Sub 5 may account for the anti-persistence in the EUR/CHF exchange rate returns.

Likewise, each sub-sample is repeatedly reshuffled for 152 times and the Hurst exponents of the shuffled sub-series are calculated. The Eq. (9) is also carried out to verify whether the original sub-samples and the shuffled sub-series share the same memory behaviors. The corresponding mean value of shuffled exponents $\langle H^s \rangle$ and p-values can be determined, as reported in Table 2. Actually, at the significance level of 1%, all the four approaches indicate that the null hypothesis can be rejected for all sub-samples except adopting BDMA and FDMA on Sub 3.

4.3. Intraday efficiency

Actually, the intraday transactions are nowadays common and surveys of market participants indicate that technical analysis is placed with more emphasis on the shorter the time horizon [77]. Also, even casual observations can clearly reveal that intraday price behavior can be vastly different from daily price behavior, as a large swing within the day can end up with little change in the end-of-day closing price. Indeed, high-frequency data are more useful for intraday analysis [78]. We take the set of the tick-by-tick transactions within one day as a sub-sample and apply the DMA and DFA methods for each sub-sample to calculate the Hurst value for each trading day. We subsequently combine them together to study the dynamic evolution the Hurst index for the entire sample period, denoted as H^d, as seen, in Fig. 6. Since there

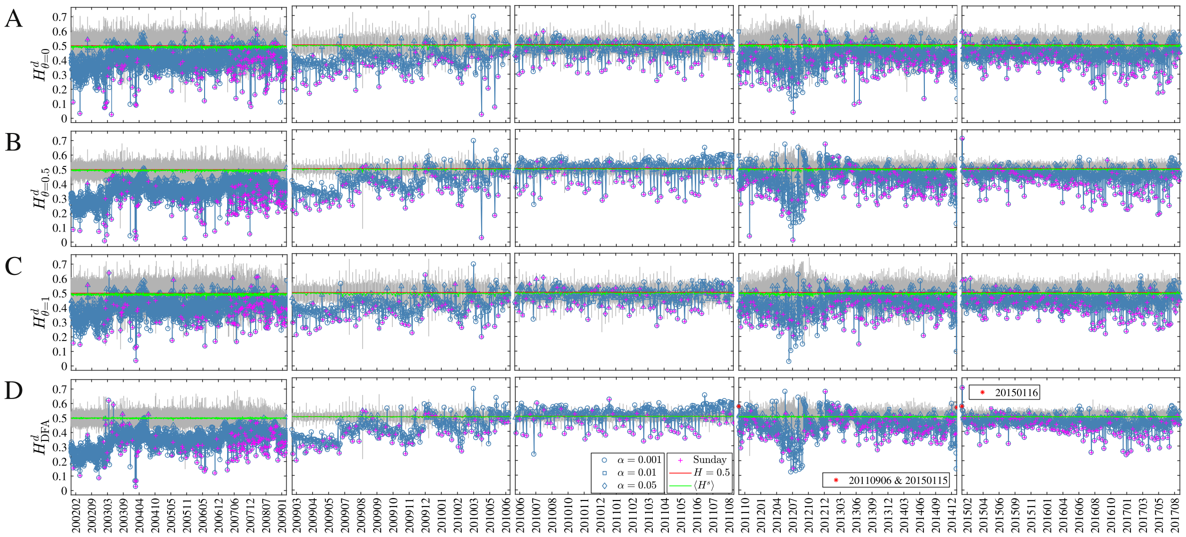

Fig. 6. The evolution of intraday Hurst exponents H^d corresponding to the five sub-samples. The shadow areas present the range of Hurst indices estimated from 152 shuffled series of intraday returns. The intraday return series indicate statistically significant weak-form inefficiency if the intraday p-value falls down beneath a fixed significance level α. (A) DMA with $\theta = 0$. (B) DMA with $\theta = 0.5$. (C) DMA with $\theta = 1$. (D) DFA.

is a negligible amount of FX activity during the weekend period, we drop the intraday observations with a length less than 500 from the sample. Totally, there exist 4642 days remaining.

Fig. 6 presents the evolution of intraday Hurst exponents H^d throughout the whole sample period, corresponding to the BDMA, CDMA, FDMA and DFA algorithms, respectively. At first glance, it is not hard to find that the presence of anti-persistence is revealed among the intraday returns of EUR/CHF, no matter what method was employed. Although the four curves of Fig. 6 approximatively maintain consistency with Eq. (8) at each trading day, the evolutionary trajectories of four curves in Fig. 6 share a remarkable similarity.

Likewise, a strict statistical test in the spirit of bootstrapping is adopted to verify the weak-form EMH for intraday returns of EUR/CHF exchange rate. Then, the original intraday series and their corresponding 152 shuffled series are analyzed with the DMA and DFA approaches to estimate the exponents H^d and H^s, which allows us to proceed the statistical tests. Broadly speaking, the time-varying $\langle H^s \rangle$ of the 152 shuffled series are coincident with the line $H = 0.5$, which corresponds to the green and red lines in Fig. 6. The shadow areas in Fig. 6 present the range of Hurst indices estimated from 152 shuffled series of intraday returns. Although the development of the exponents H^d exhibits large fluctuations and intermittent behavior in each panel of Fig. 6, a large number of the fluctuations are within the shadow area, especially in the second half of the entire sample. Following Eq. (9), the intraday return series indicate statistically significant weak-form inefficiency if the intraday p-value falls down beneath a fixed significance level α, in which the persistence or anti-persistence can be identified. Correspondingly, three significance levels (α=0.001, 0.01, 0.05) are embed in Fig. 6, which are represented by three different markers. Roughly, the vast majority of intraday returns indicate a rejection of the weak-form EMH for CDMA and DFA, while a relatively small number of intraday H^d present rejection of the weak-form EMH for BDMA and FDMA. Hence, a further statistical analysis was conducted for the investigation of H^d.

Table 3 reports the range of intraday Hurst exponents H^d and intraday p-values p^d of the four methods, covering the full sample and five sub-samples. $\langle H^d \rangle$ is the average value of H^d and shows a downward departure from 0.5 regardless of the adopted approaches, which provides further evidence for the presence of anti-persistence in most intraday returns of EUR/CHF exchange rate. ρ is the ratio of the number of H^d or p^d dropping in a fixed interval within the total 4642 trading days. The exponent H^d mainly concentrates in the ranges $(0,\ 0.4]$ and $(0.4,\ 0.5)$. Besides, the whole p-values reveal that there exist 49.55%, 77.08%, 47.57% and 78.91% of intraday returns appearing significant weak-form inefficiency, corresponding to BDMA, CDMA, FDMA and DFA methods, respectively. Overall, whatever the method, the statistically significant weak-form inefficiency appears at an approaching to 50% of intraday returns throughout the whole sample.

Additionally, Fig. 6 can meticulously depict the memory behaviors in local samples. For Sub 1, the vast majority of intraday Hurst exponents H^d are less than 0.5, especially at the beginning, which indicates a sequential anti-persistence of EUR/CHF exchange rate market. Explanatorily, the initial stage of EUR/CHF exchange rate may account for anti-persistence of Sub 1, together with some significant financial events. A relatively strong anti-persistence is found throughout Sub 2, which can be caused by the SNB's intervention. When it comes to Sub 3, the intraday Hurst exponents H^d show a vibration around 0.5, corresponding to the "free float" period. Also, Sub 4 presents that most of intraday returns of EUR/CHF reveal the anti-persistence. After the SNB's announcement of enforcing a minimum exchange rate of 1.20 Swiss francs per one euro, there is a sharp drop in the values of H^d correspondingly. Finally, with termination of the Swiss

Table 3
The distribution of intraday Hurst exponents H^d and intraday p-values p^d for the four methods, covering the full sample and five sub-samples. ρ is the ratio of the number of H^d or p^d dropping in a fixed interval to the total trading days 4642. $\langle H^d \rangle$ is the average value of H^d.

		Whole	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5
BDMA	$\langle H^d \rangle$	0.4158	0.3982	0.4547	0.4245	0.4270	0.4323
	$\rho_{0.5<H^d\leq 0.6}$	434/4642	105/2257	105/396	63/383	103/1049	58/557
	$\rho_{0.4<H^d<0.5}$	2500/4642	1067/2257	218/396	189/383	657/1049	369/557
	$\rho_{0<H^d\leq 0.4}$	1703/4642	1083/2257	71/396	131/383	288/1049	130/557
	$\rho_{0.01\leq p^d<0.05}$	588/4642	312/2257	32/396	55/383	116/1049	73/557
	$\rho_{0.001\leq p^d<0.01}$	292/4642	140/2257	20/396	22/383	71/1049	39/557
	$\rho_{0\leq p^d<0.001}$	1420/4642	845/2257	66/396	112/383	254/1049	143/557
CDMA	$\langle H^d \rangle$	0.4048	0.3548	0.4788	0.4556	0.4433	0.4472
	$\rho_{0.5<H^d\leq 0.6}$	541/4642	12/2257	184/396	134/383	155/1049	56/557
	$\rho_{0.4<H^d<0.5}$	2071/4642	629/2257	159/396	158/383	692/1049	433/557
	$\rho_{0<H^d\leq 0.4}$	2019/4642	1615/2257	51/396	89/383	196/1049	68/557
	$\rho_{0.01\leq p^d<0.05}$	293/4642	59/2257	46/396	40/383	99/1049	49/557
	$\rho_{0.001\leq p^d<0.01}$	201/4642	56/2257	20/396	19/383	64/1049	42/557
	$\rho_{0\leq p^d<0.001}$	3084/4642	2033/2257	148/396	200/383	454/1049	249/557
FDMA	$\langle H^d \rangle$	0.4197	0.4006	0.4611	0.4276	0.4324	0.4386
	$\rho_{0.5<H^d\leq 0.6}$	466/4642	103/2257	113/396	69/383	116/1049	65/557
	$\rho_{0.4<H^d<0.5}$	2533/4642	1078/2257	218/396	186/383	675/1049	376/557
	$\rho_{0<H^d\leq 0.4}$	1635/4642	1072/2257	63/396	128/383	257/1049	115/557
	$\rho_{0.01\leq p^d<0.05}$	525/4642	267/2257	41/396	61/383	87/1049	69/557
	$\rho_{0.001\leq p^d<0.01}$	331/4642	182/2257	20/396	32/383	60/1049	37/557
	$\rho_{0\leq p^d<0.001}$	1357/4642	826/2257	55/396	101/383	243/1049	132/557
DFA	$\langle H^d \rangle$	0.4076	0.3510	0.4903	0.4671	0.4516	0.4548
	$\rho_{0.5<H^d\leq 0.6}$	620/4642	14/2257	218/396	145/383	182/1049	61/557
	$\rho_{0.4<H^d<0.5}$	2003/4642	567/2257	134/396	155/383	702/1049	445/557
	$\rho_{0<H^d\leq 0.4}$	2005/4642	1675/2257	41/396	78/383	160/1049	51/557
	$\rho_{0.01\leq p^d<0.05}$	277/4642	46/2257	44/396	33/383	106/1049	48/557
	$\rho_{0.001\leq p^d<0.01}$	175/4642	29/2257	21/396	21/383	71/1049	33/557
	$\rho_{0\leq p^d<0.001}$	3211/4642	2125/2257	156/396	207/383	465/1049	258/557

franc's one-sided target zone, Sub 5 also indicates anti-persistence for most intraday returns of EUR/CHF exchange rate. In a word, these phenomena further demonstrate that the effectiveness of the EUR/CHF exchange rate market in local periods is reduced when the market falls into a turbulent state. Remarkably, the intraday exponents H^d of Sunday exhibit quite different memory behaviors from the results of other trading days in Fig. 6. In addition, the Forex market remains sleepless, 24 h a day, trading from 22:00 GMT on Sunday (Sydney) until 22:00 GMT Friday (New York).[3] Obviously, an overwhelming majority of the downward spikes of exponents H^d emerged on Sunday, which represented a relatively strong anti-persistence. Explanatorily, the relatively few observations of intraday returns can be accounted for this periodic phenomenon occurring on Sunday. More concretely, a small amount of intraday transactions can affect the spread of information in the FX markets, which thus decreases the efficiency of the EUR/CHF exchange rate market.

5. Conclusion

It is a stylized fact that the Swiss franc is a safe haven currency. Inspired by the monetary policy that the SNB imposed a minimum exchange rate of 1.20 Swiss francs per one euro from 6 September 2011 to 15 January 2015, this paper comprehensively re-examines the validity of the weak-form EMH for the EUR/CHF exchange rate market using the tick-by-tick data. Specifically, the market efficiency of full sample, five sub-samples and intraday samples are investigated. Besides, two nonparametric methods DMA and DFA together with a strict statistical test are adopted to verify the determinacy of each estimated Hurst exponent.

As mentioned above, five episodes of different monetary policy regimes are distinguished according to the SNB's Quarterly Bulletins, which can been roughly split into two "free float" periods and three "intervention" periods. Both Jarque–Bera test and Anderson-Darling test reveal that the whole sample and five sub-samples of EUR/CHF exchange rate returns do not accord with normal distribution, characterizing with a leptokurtic. The critical Hurst index $H = 0.5$ is used as a benchmark to identify the persistence or anti-persistence in high-frequency EUR/CHF exchange rate return series. Performing the statistical tests on the whole sample demonstrates the presence of extremely mild anti-persistence of the EUR/CHF exchange rate market in the investigated period 2002–2017, which can be roughly regarded that the studied markets achieve efficiency to some extent. Statistical tests have also been carried out on five sub-samples and 4642 intraday samples. For five fixed sub-samples, the anti-persistence is revealed for almost every sub-samples except Sub 3. In contrast, an extremely weak persistence was uncovered in Sub 3. Presumably, the SNB's policy interventions

3 https://en.wikipedia.org/wiki/Foreign_exchange_market.

and regular financial turbulence may have involvement with the mild inefficiency in the EUR/CHF exchange rate return series, which suggests that further improvement in information efficiency can be achieved by relaxing foreign exchange market regulations.

When it comes to the intraday efficiency of EUR/CHF exchange rate return series, an alternate anti-persistence and persistence is observed during the full sample, which means the intraday returns can be either antipersistent, persistent, or uncorrelated. It is not hard to find that the presence of anti-persistence is revealed among the most intraday returns of EUR/CHF exchange rate, no matter what method is employed. Moreover, the intraday Hurst exponents H^d mainly concentrates in the ranges of $(0,\ 0.4]$ and $(0.4,\ 0.5)$. The exponents H^d estimated by CDMA and DFA lend credence to the arguments in support of market anti-persistence. Recalling the evolution of exponents H^d, we find that the lower bound 1.2 on EUR/CHF announced by the SNB can be roughly regarded as a turning point of the market efficiency. In particular, the relatively few observations of intraday returns can be accounted for this periodic phenomenon occurring on Sunday.

Overall, an weak anti-persistence or inefficiency is characterized for the high-frequency return series of EUR/CHF exchange rate in most period, which was in nice agreement with the antipersistent pricing behavior of high-frequency Asian FX rates [54]. These results further reveal that the EUR/CHF exchange rate market requires a certain time to digest the high-frequency trading information.

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