

**SOME STYLISED FACTS ABOUT
THE EXCHANGE RATE BEHAVIOUR
OF CENTRAL EUROPEAN CURRENCIES¹**

DOI: 10.18267/j.aop.525

Jan Vejmelek***Abstract**

The paper investigates developments of exchange rate time series of Central European currencies and tries to find evidence of some stylised facts. Statistical methods and an econometric approach to the univariate time series modelling of high-frequency data, i.e., daily, are used.

The main conclusions are as follows: (1) All the CE nominal exchange time series are not stationary; nevertheless, stationarity of all the return time series was confirmed. (2) Volatility clustering was proven and the GARCH modelling approach was successfully applied, including asymmetric modelling of volatility. (3) The more flexible an exchange rate regime is, the more volatile the respective currency. This is true for both nominal and real exchange rates. While nominal volatility is lower than real volatility in a system of fixed or less flexible exchange rates, the opposite is true for flexible systems: exchange rate volatility is higher in nominal terms than in real terms.

Keywords: exchange rate, volatility, time series analysis, GARCH models

JEL Classification: C22, F31

Introduction

Financial markets behave in such a way that the time series of prices (or yields) of financial market instruments often demonstrate some behaviour or characteristics that can be generalised for a similar type of univariate or multivariate time series. Observations or empirical results that are generally accepted as being true are called stylised facts. Sewell [2011] defines stylised facts as empirical findings that are so consistent that they are accepted as true. The dictionary on About.com adds that stylised facts are observations that have been made in so many contexts that they are widely understood to be empirical truths to which theories must adhere.

We will focus on some stylised facts of the exchange rate time series behaviour in this article. Thus, we will not follow mainstream macro or micro exchange rate

¹ The paper is a part of research project no. F1/05/2014 Financial and Economic Cycle supported by the Internal Grant Agency of the University of Economics, Prague.

* Faculty of Finance and Accounting, University of Economics, Prague; Chief Economist, Komerční banka, a.s. (jan_vejmelek@kb.cz).

models² but rather models based on the behavioural finance framework. The key theoretical assumption is that agents have cognitive limitations, i.e., their decisions are based on the rule of thumb (heuristic forming of expectations). However, it does not mean that agents behave irrationally: they are willing to learn and adjust their behaviour [De Grauwe and Kaltwasser, 2012].

Stylised facts of exchange rate development are mainly researched for major currencies.³ We will focus on the behaviour of Central European currencies (CE currencies) in this paper. Central European countries went through a long period of transition to market-oriented economies and a wide range of exchange rate systems. The aim of the paper is to investigate the (statistical) behaviour of the respective currencies. Specifically, the typical behaviour of the Czech, Polish, Hungarian and Slovak currencies quoted against the euro, which is the reference currency for all the Central European countries, and other indicators linked to exchange rates will be investigated.

The structure of the paper is as follows: after a brief description of the data used (Chapter 1), we will focus on the distribution characteristics of exchange rate returns (Chapter 2). Then we will move on to heteroskedasticity and volatility modelling in Chapter 3 and a discussion of differing volatility in different exchange rate regimes (Chapter 4). Chapter 5 summarises the final conclusions.

1. Description of data used

Daily nominal exchange rate data for EUR/CZK, EUR/HUF, EUR/PLN and EUR/SKK⁴ were taken from the DataStream database for the period from 1999 to 2014. In some cases, data before 1999 were used and are described in the respective chapters of this paper. Monthly time series of real effective exchange rates of CZK, HUF, PLN and SKK are also taken from the DataStream database; the primary source is the OECD database.

2. Normal versus fatter-tail distribution of exchange rate returns

In this section, we will focus on pure time series of exchange rate data (univariate time series analysis). Financial time series, as well as exchange rate time series, are characterised by properties and shapes given by the microstructure of the financial market (or FX market, respectively). As a result, the dynamics of such a time series are more influenced by non-systematic factors, leading to relatively high volatility unstable in time, resulting in a conditional non-stationarity of the time series [Arlt and Arltová, 2001].

Not only time-varying variability but also the long-term trend is behind the non-stationarity of CE currencies (this is clearly visible in Figure 1), which is the result of convergence processes of the Central European region toward the eurozone's economic levels (and is even more visible in time series of real exchange rates⁵ of CE currencies; see Figure 2).

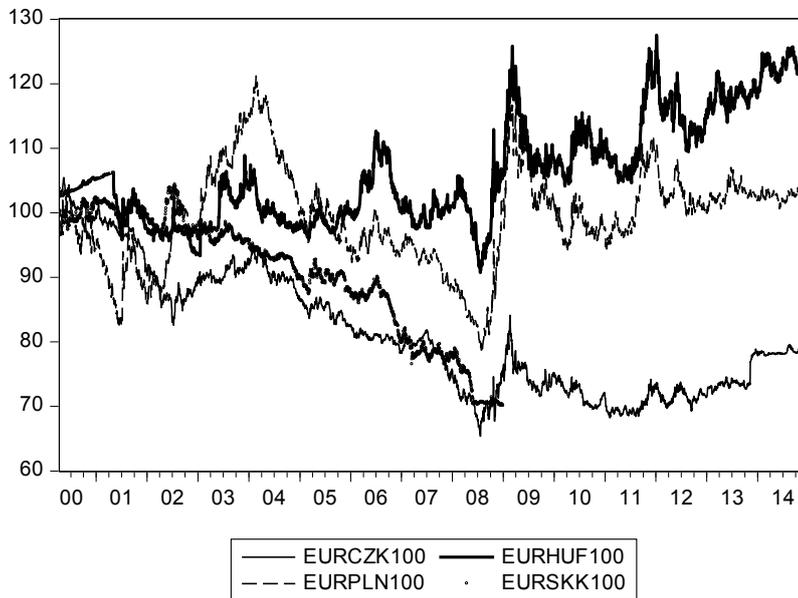
2 A review of the traditional macro or micro approach to the exchange rate modelling can be found, for example, in James et al. [2012].

3 For example, Lothian [1998] focuses on exchange rate behaviour of OECD currencies.

4 Currency pairs are quoted in terms of units of the respective Central European currency per unit of EUR.

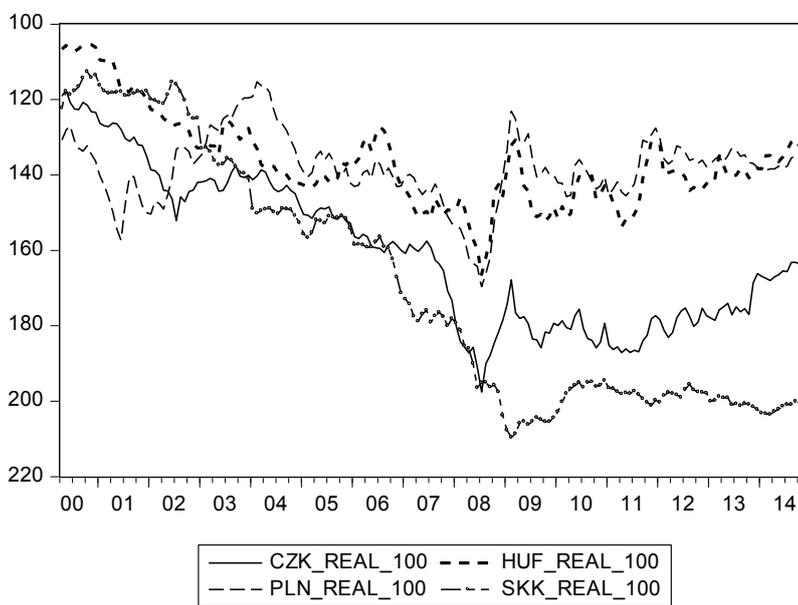
5 Actually, real exchange rate movements are what investors follow. However, high-frequency data are available only in nominal terms.

Figure 1| Exchange rate development of CE currencies (4 Jan 1999 = 100), in nominal terms



Source: Author's calculations based on data from Bloomberg

Figure 2| Exchange rate development of CE currencies (January 1995 = 100), in real terms



Source: Author's calculations based on data from the DataStream database

The summary statistic of the EUR/CZK exchange rate (first row of Table 1 – summary statistic) highlights a slight negative skewness and low kurtosis. The EUR/CZK time series is not normal at the 99% confidence interval according to the Jarque-Bera statistic. Consequently, the Augmented Dickey Fuller Test (Table 2 – unit root tests) clearly shows that we cannot reject the hypothesis of a unit root, i.e., the EUR/CZK time series is non-stationary and some transformation is needed. The conclusion of non-stationarity is also valid for the EUR/PLN, EUR/HUF and EUR/SKK time series at the 5% significance level.

Table 2| Summary statistics

Exchange rate	Sample period	Number of observations	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Probability
EUR/CZK	1/1/99 – 31/12/14	4171	29.15987	28.21	38.633	22.945	3.884591	0.568583	2.187653	339.4241	0
EUR/HUF	4/1/99 – 31/12/14	4109	266.513	260.94	320.78	228.16	20.54391	0.732029	2.474301	414.2945	0
EUR/PLN	4/1/99 – 31/12/14	4109	4.058215	4.0812	4.9346	3.2053	0.299227	-0.100005	3.296354	21.88548	0.000018
EUR/SKK	4/1/99 – 31/12/08	2560	39.51241	40.91	47.484	30.126	4.154182	-0.769149	2.540462	274.9372	0

Source: Author's calculations based on data from the Bloomberg database

Table 2| Unit root tests

Exchange rate	Augmented Dickey-Fuller Test statistic		Phillips-Perron Test statistic	
	t-Statistic	Probability*	Adjusted t-Statistic	Probability*
EUR/CZK	-1.138541 [#]	0.2326	-1.157815 [#]	0.2258
EUR/HUF	-3.597028 ^{##}	0.0301	-3.257387 ^{##}	0.0736
EUR/PLN	-2.618106 ^{###}	0.0893	-2.446589 ^{###}	0.1291
EUR/SKK	-2.158702 ^{##}	0.5120	-2.272655 ^{##}	0.4483

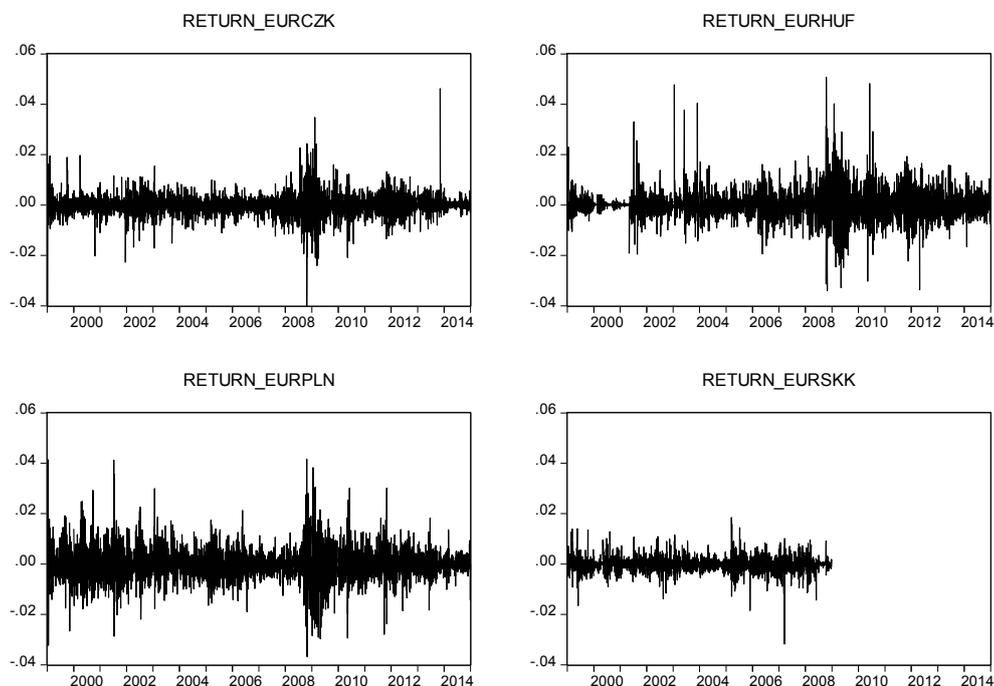
*MacKinnon (1996) one-sided p-values, [#] without trend and intercept, ^{##} with trend and intercept, ^{###} with intercept

Source: Author's calculations based on data from the DataStream database

The natural method of stationarisation is a transformation of the exchange rate time series into the rates of return time series.⁶ Table 3 clearly shows that the EUR/CZK, EUR/HUF, EUR/PLN and EUR/SKK return time series are stationary, as the Augmented Dickey Fuller Test and Phillips-Perron Test statistics confirm.

6 Actually, we used another common method of transformation: the logarithmic transformation, i.e., $rt = \ln St - \ln St-1$.

Figure 3| Exchange rate returns time series



Source: Author's calculations based on data from the DataStream database

Table 3| Unit root tests

Exchange rate	Augmented Dickey-Fuller Test statistic [#]		Phillips-Perron Test statistic [#]	
	t-Statistic	Probability*	Adjusted t-Statistic	Probability*
Return of EUR/CZK	-70.43882	0.0001	-70.70412	0.0001
Return of EUR/HUF	-62.68021	0.0001	-63.14030	0.0001
Return of EUR/PLN	-46.01267	0.0001	-62.54014	0.0001
Return of EUR/SKK	-46.66404	0.0001	-46.65288	0.0001

*MacKinnon [1996] one-sided p-values, [#] without trend and intercept

Source: Author's calculations based on data from the DataStream database

One of the assumptions in the classical analysis of time series is that the return transformation has a normal distribution.

The summary statistics for the EUR/CZK returns presented in Figure 4 illustrate a negligible negative skewness (big negative returns are slightly more probable than big positive returns) and a very high kurtosis (log returns are significantly more peaked than normal distribution). The later is in compliance with findings of Bubák

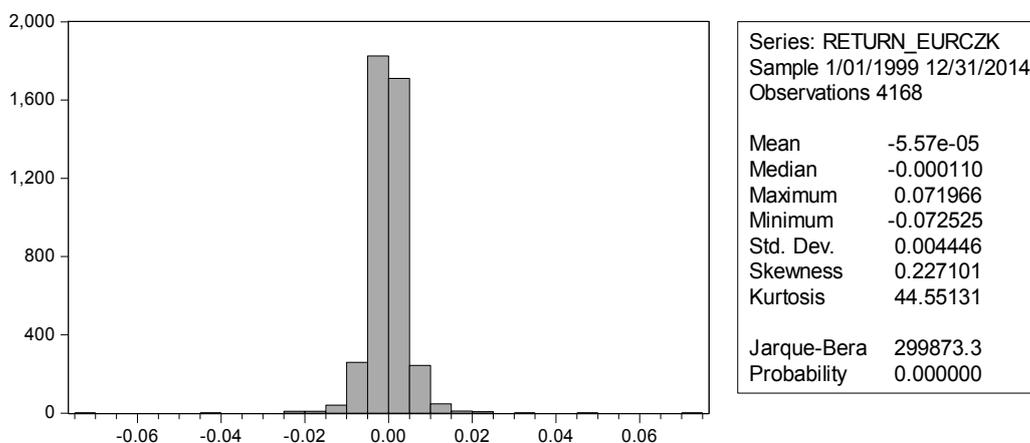
& Žikeš [2009]; thus, it is not a surprise that the Jarque-Bera test confirms non-normality of the EUR/CZK return series. As the PLN, HUF and SKK behave in a similar way, we can conclude that a feature of Central European exchange rates shows the same characteristics that are typical for high-frequency financial time series data, i.e., exchange rate returns' distributions have fat tails, implying that the probabilities of extremely high and extremely low returns are higher than in the case of normal distribution. The PLN and HUF showed a positive skewness, implying that big positive returns are more probable than big negative returns.

Table 4| Summary statistics of the exchange rate return time series

Exchange rate	Number of observations	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Probability
Return of EUR/CZK	4168	-5.57E-05	-0.00011	0.071966	-0.072525	0.004446	0.227101	44.55131	299873.3	0.000
Return of EUR/HUF	4066	6.57E-05	-3.90E-05	0.050693	-0.033885	0.005717	0.750415	11.99828	14099.11	0.000
Return of EUR/PLN	4066	1.39E-05	-0.000212	0.041636	-0.036798	0.006363	0.458517	8.17698	4683.028	0.000
Return of EUR/SKK	2528	-0.000135	-0.000165	0.0185	-0.031801	0.003031	-0.19063	11.89614	8351.536	0.000

Source: Author's calculations based on data from the DataStream database

Figure 4| Summary statistic for EUR/CZK returns



Source: Author's calculations based on data from the DataStream database

3. Heteroskedasticity modelling of CE exchange rates movements

The other key assumption of classical time series analysis is that returns behave like a white noise process, i.e., that returns are not correlated, identically distributed with zero means and constant variance (or a strict white noise process, requiring not only non-correlation but independence).

The EUR/CZK return time series⁷ is presented in Figure 3 (upper left graph). It is clearly seen that a common characteristic of the return time series is not constant but time-changing volatility (variability). Thus, the time series is heteroskedastic. It changes in clusters [Mandelbrot, 1963], i.e., sometimes volatility changes in very short time periods and sometimes it is stable for a longer period of time.

Changing volatility should be modelled using a group of so-called Generalised Autoregressive Conditional Heteroskedasticity models (GARCH models).⁸ GARCH models are based on the Box-Jenkins approach to volatility modelling. Every GARCH model consists of two equations: (1) a conditional mean equation, and (2) a conditional variance equation. An example of the mean equation is as follows:

$$Y_t = c + X_t' \theta + e_t, \quad (1)$$

i.e., the dependent variable Y_t (which will be the return r_t in our case) is modelled as a function of the explanatory variables X_t' and an error term e_t equal to $\sigma_t \varepsilon_t$, where ε_t is the *iid* variable with a zero mean and unity variance, while c is a constant. Volatility σ_t^2 is not constant and is modelled by the conditional variance equation:

$$\sigma_t^2 = \omega + \sum_{j=1}^q \beta_j \sigma_{t-j}^2 + \sum_{i=1}^q \alpha_i \varepsilon_{t-i}^2, \quad (2)$$

which is an expression of the GARCH(p,q) model. ω represents a constant term, σ_{t-j}^2 is $t-j$ period lagged volatility (the so-called GARCH term) and ε_{t-i}^2 (the ARCH term) is a variable measuring the last forecasting error or capturing news about volatility from the $t-j$ period.

We have applied the GARCH approach to the time series of CE currency returns. In all the cases, the GARCH (1,1) model was the most suitable. The results are depicted in Table 5.

Taking a look at Panel A of Table 5, it is quite obvious that the GARCH (1,1) model is suitable for modelling daily returns of all the CE currencies as all the coefficients in the conditional variance equations are statistically significant and comply with the assumptions. Regarding the conditional mean equations, the constant is not statistically significant in the case of the EUR/CZK and EUR/HUF time series. Thus, the daily return of exchange rate time series can be decrypted using the following expressions:

EUR/CZK: $r_t = e_t$, $e_t = \sigma_t \varepsilon_t$, $\sigma_t^2 = 0.000000614 + 0.137602e_{t-1}^2 + 0.832790\sigma_{t-1}^2$;

EUR/HUF: $r_t = e_t$, $e_t = \sigma_t \varepsilon_t$, $\sigma_t^2 = 0.000000331 + 0.059899e_{t-1}^2 + 0.930985\sigma_{t-1}^2$;

EUR/PLN: $r_t = -0.000150 + e_t$, $e_t = \sigma_t \varepsilon_t$, $\sigma_t^2 = 0.000000388 + 0.090082e_{t-1}^2 + 0.902635\sigma_{t-1}^2$;

EUR/SKK: $r_t = -0.000120 + e_t$, $e_t = \sigma_t \varepsilon_t$, $\sigma_t^2 = 0.000000251 + 0.105633e_{t-1}^2 + 0.877734\sigma_{t-1}^2$.

7 However, the return coming from the spot exchange movement is a result of the spot-spot speculation, i.e., intraday speculation. For longer duration of the opened positions (more than one day), interest rate differential must be taken into account. Theoretically, market players follow uncovered interest rate parity condition.

8 GARCH models introduced by Bollerslev [1986] and Taylor [1986] generalised the Autoregressive Conditional Heteroskedasticity model (ARCH model) of Engle [1982].

Table 5| Application of the GARCH approachConditional mean equation: $r_t = c + e_t$;Conditional variance equation: $\sigma_t^2 = \alpha_0 + \alpha_1 e_{t-1}^2 + \beta_1 \sigma_{t-1}^2$ ($\alpha_0 > 0$, $\alpha_1, \beta_1 \geq 0$, $\alpha_1 + \beta_1 < 1$).

Panel A				
Coefficient (standard error)	EUR/CZK	EUR/HUF	EUR/PLN	EUR/SKK
c	-6.37.10 ^{-5*} (5.01.10 ⁻⁵)	0.000103* (0.000102)	-0.000150 (7.07.10 ⁻⁵)	-0.000120 (5.03.10 ⁻⁵)
α_0	6.14.10 ⁻⁷ (1.56.10 ⁻⁷)	3.31.10 ⁻⁷ (1.59.10 ⁻⁷)	3.88.10 ⁻⁷ (9.80.10 ⁻⁷)	2.51.10 ⁻⁷ (1.09.10 ⁻⁷)
α_1	0.137602 (0.016059)	0.059899 (0.026051)	0.090082 (0.011508)	0.105633 (0.020471)
β_1	0.832790 (0.015604)	0.930985 (0.021962)	0.902635 (0.011035)	0.877734 (0.024562)
Panel B – ARCH test				
F-Statistic	0.082216	0.006280	2.533284	0.001005
Prob. F	0.7743	0.9368	0.1115	0.9747
Obs.*R-squared	0.082254	0.006283	2.532952	0.001006
Prob. Chi-squared(1)	0.7743	0.9368	0.1115	0.9747
Panel C – Normality test of standardised residuals				
Jarque-Bera	65661.40	186925.4	704.3514	8832.990
Probability	0.00000	0.00000	0.00000	0.00000

Source: Author's calculations based on data from the DataStream database, *not significant

Q-tests of the standardised models verify the respective GARCH models. Also, the ARCH-LM test (see Panel B in Table 5) shows that there is no other ARCH structure in the respective models. Only the distributions of standardised residuals are not normal according to the Jarque-Bera tests (see Panel C in Table 5) because of too high kurtosis.

The GARCH model is the first step in modelling volatility with its own assumptions and limitations. There are more and more models based on the GARCH approach that relax the origin assumptions and develop models further. For a comprehensive discussion, see Green [2008] or Enders [2010].

Modelling exchange rate volatility represents a growing area in literature, including the Central European region. Exchange rate volatility is modelled using simple GARCH models or extended or modified GARCH models; modelled volatility is then explained by various determinants such as different FX regimes [Kočenda and Valachy, 2006 – using T-GARCH model⁹], estimated target exchange rate [Fidrmuc and Horváth, 2008 – using GARCH and extended TARCH models], or optimal currency area criteria [Horváth, 2005]. The GARCH (1,1) process for EUR/CZK exchange rate returns was used by Fišer & Horváth [2010] for examining the effects of the Czech National Bank's

9 Or changes between volatility regimes, respectively [Frömmel, 2010 – using Markow-Switching GARCH model].

communication, macroeconomic news and exchange rate differentials on exchange rate volatility.

One of the advantages of the above-mentioned T-GARCH model (or threshold model or GRJ model) is that it allows us to model asymmetric behaviour, where positive and negative errors can have a different impact on volatility. The T-GARCH (1,1) model should have the following form:

$$r_t = c + e_t, e_t = \sigma_t \epsilon_t, \sigma_t^2 = \alpha_0 + \alpha_1 e_{t-1}^2 + \beta_1 \sigma_{t-1}^2 + \gamma_1 e_{t-1}^2 I_{t-1}, I_t = 1 \text{ for } e_t < 0, 0 \text{ others.} \quad (3)$$

Having applied the T-GARCH (1,1) model to CE currencies, we have found that the model was suitable for modelling the volatility of EUR/HUF and EUR/PLN time series only.¹⁰ The outcome is depicted in Table 6 below:

Table 6| Application of the T-GARCH approach

Conditional mean equation: $r_t = c + e_t$;

Conditional variance equation: $\sigma_t^2 = \alpha_0 + \alpha_1 e_{t-1}^2 + \beta_1 \sigma_{t-1}^2 + \gamma_1 e_{t-1}^2 I_{t-1}, I_t = 1 \text{ for } e_t < 0, 0 \text{ others.}$

Panel A				
Coefficient (standard error) [#]	EUR/CZK	EUR/HUF	EUR/PLN	EUR/SKK
c	-7.53.10 ^{-5**} (5.22.10 ⁻⁵)	0.000148** (9.92.10 ⁻⁵)	-6.63.10 ^{-5*} (7.30.10 ⁻⁵)	-0.000131 (4.91.10 ⁻⁵)
α_0	6.17.10 ⁻⁷ (1.64.10 ⁻⁷)	4.63.10 ^{-7*} (2.62.10 ⁻⁷)	4.56.10 ⁻⁷ (9.89.10 ⁻⁸)	2.42.10 ⁻⁷ (1.06.10 ⁻⁷)
α_1	0.123438 (0.023630)	0.102564 (0.027937)	0.118993 (0.015790)	0.097875 (0.025659)
β_1	0.829929 (0.017092)	0.916798 (0.016850)	0.903780 (0.009828)	0.877335 (0.024428)
γ_1	0.035321** (0.031497)	-0.068331 (0.022715)	-0.069007 (0.019175)	0.020279** (0.047428)
Panel B – ARCH test				
F-Statistic	0.068774	0.003610	0.743809	0.007284
Prob. F	0.7931	0.9521	0.3885	0.9320
Obs.*R-squared	0.068806	0.003611	0.744039	0.007290
Prob. Chi-squared(1)	0.7931	0.9521	0.3884	0.9320
Panel C – Normality test of standardised residuals				
Jarque-Bera	65943.50	170445.6	577.0782	8176.070
Probability	0.0000	0.0000	0.0000	0.0000

[#] Note: quasi-maximum likelihood (QML) covariances and standard errors are presented using the methods described by Bollerslev & Wooldridge [1992].

* not significant at 5%, ** not significant at 10%

Source: Author's calculations based on data from the DataStream database

10 Maybe surprisingly, the leverage effect is not significant for the Czech and Slovak currencies, i.e., for countries where the nominal convergence has gone through the nominal exchange rate appreciation.

The leverage factor is present in the EUR/HUF and EUR/PLN time series;¹¹ however, the coefficients are not very high. Q-tests of the standardised models verify these two T-GARCH models. Also the ARCH-LM test (see Panel B in Table 6) shows that there is no other ARCH structure in the respective models. Again, only the distributions of standardised residuals are not normal according to Jarque-Bera tests (see Panel C in Table 6) because of too high kurtosis. Thus, the daily return of the EUR/HUF and EUR/PLN exchange rate time series can be described using the following expressions:

EUR/HUF:

$$r_t = e_t, \\ e_t = \sigma_t \epsilon_t, \sigma_t^2 = 0.000000463 + 0.102564e_{t-1}^2 + 0.916798\sigma_{t-1}^2 - 0.068331e_{t-1}^2 I_{t-1}, \\ I_t = 1 \text{ for } e_t < 0, 0 \text{ others.}$$

EUR/PLN:

$$r_t = -0.0000663 + e_t, \\ e_t = \sigma_t \epsilon_t, \sigma_t^2 = 0.000000456 + 0.118993e_{t-1}^2 + 0.903780\sigma_{t-1}^2 - 0.069007e_{t-1}^2 I_{t-1}, \\ I_t = 1 \text{ for } e_t < 0, 0 \text{ others.}$$

While the leverage factor is assumed to be quadratic in the T-GARCH model, another approach to modelling the asymmetry was proposed by Nelson [1991]. He proposed an exponential leverage effect. That is why the model is called the Exponential GARCH or E-GARCH model. The E-GARCH (1,1) model should have the following form [Cipra, 2008]:

$$r_t = c + e_t, e_t = \sigma_t \epsilon_t, \ln \sigma_t^2 = \alpha_0 + \alpha_1 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + \beta_1 \ln \sigma_{t-1}^2 + \gamma_t \frac{e_{t-1}}{\sigma_{t-1}}. \quad (4)$$

Asymmetry is present in the case of $\gamma_t \neq 0$ for the special case of the leverage effect $\gamma_t < 0$. Application of the E-GARCH approach to CE currencies is summarised in Table 7.

The asymmetry was confirmed for all the considered currency pairs with the exception of EUR/SKK, where the parameter γ is not statistically significant. For EUR/CZK, the leverage effect was confirmed. Thus, based on the E-GARCH modelling, the rate time series of CE exchange rates can be described using the following expressions:

EUR/CZK:

$$r_t = -0.000101 + e_t, e_t = \sigma_t \epsilon_t, \ln \sigma_t^2 = -0.458947 + 0.205607 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + 0.973208 \ln \sigma_{t-1}^2 - 0.015848 \frac{e_{t-1}}{\sigma_{t-1}}.$$

EUR/HUF:

$$r_t = 0.000131 + e_t, e_t = \sigma_t \epsilon_t, \ln \sigma_t^2 = -0.356978 + 0.145435 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + 0.976797 \ln \sigma_{t-1}^2 + 0.043238 \frac{e_{t-1}}{\sigma_{t-1}}.$$

EUR/PLN:

$$r_t = e_t, e_t = \sigma_t \epsilon_t, \ln \sigma_t^2 = -0.359555 + 0.183930 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + 0.979199 \ln \sigma_{t-1}^2 + 0.058809 \frac{e_{t-1}}{\sigma_{t-1}}.$$

EUR/SKK:

$$r_t = -0.000147 + e_t, e_t = \sigma_t \epsilon_t, \ln \sigma_t^2 = -0.614646 + 0.228885 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + 0.962271 \ln \sigma_{t-1}^2.$$

11 It can be explained by higher EUR/PLN and EUR/HUF exchange rate volatility in comparison with EUR/CZK and EUR/SKK and/or by higher interest rates on both currencies, which support investors' taking position in carry trades, i.e., long in the high-yielding currency / short in EUR.

Table 7 | Application of the E-GARCH approach

Conditional mean equation: $r_t = c + e_t$
 Conditional variance equation: $\ln \sigma_t^2 = \alpha_0 + \alpha_1 \left| \frac{e_{t-1}}{\sigma_{t-1}} \right| + \beta_1 \frac{e_{t-1}}{\sigma_{t-1}} + \gamma_1$.

Panel A				
Coefficient (standard error)	EUR/CZK	EUR/HUF	EUR/PLN	EUR/SKK
c	-0.000101 (4.24.10 ⁻⁵)	0.000131 (4.29.10 ⁻⁵)	-0.000117* (7.12.10 ⁻⁵)	-0.000147 (4.59.10 ⁻⁵)
α_0	-0.458947 (0.038470)	-0.356978 (0.021161)	-0.359555 (0.040844)	-0.614646 (0.051749)
α_1	0.205607 (0.013673)	0.145435 (0.007114)	0.183930 (0.016141)	0.228885 (0.016304)
β_1	0.973208 (0.002916)	0.976797 (0.001526)	0.979199 (0.003387)	0.962271 (0.003885)
γ_1	-0.015848 (0.008005)	0.043238 (0.005817)	0.058809 (0.009767)	0.004729* (0.008101)
Panel B – ARCH test				
F-Statistic	0.001422	0.075989	2.073401	0.024682
Prob. F	0.9699	0.7828	0.1500	0.8752
Obs.*R-squared	0.001423	0.076025	2.073364	0.024701
Prob. Chi-squared(1)	0.9699	0.7828	0.1499	0.8751
Panel C – Normality test of standardised residuals				
Jarque-Bera	56392.10	1167198	614.7385	14348.07
Probability	0.000000	0.000000	0.000000	0.000000

Note: Assumed Generalised error distribution (GED) of ϵ_t with the parameter equal to 1.5.

* not significant

Source: Author's calculations based on data from the DataStream database

4. Volatility of CE exchange rate movements versus exchange rate systems

Up to now, volatility properties of unilateral time series of exchange rates or volatility clustering in high-frequency time series (daily in our case) were discussed, respectively. Let us now move on to an investigation of the relationship between the volatility of the nominal and real exchange rates on the one hand and the regime of the respective exchange rate on the other. It is another stylised fact that when exchange rates are flexible, they tend to be more volatile.¹² We have investigated the volatility of CE currencies in different exchange rate regimes.

Since the early 1990s, CE countries have undergone different exchange regimes over the past two decades on the way from planned to market-oriented economies. For all the CE countries, a move from non-convertible to convertible currencies is typical for the first few years of transition. Regarding exchange rate regimes, a move from fixed or less flexible systems (a wide range of peg systems used to be applied quite often) to the much more flexible or even float system typical of the recent years. The only exception

¹² A conclusion pioneered by Mussa [1986].

is Slovakia, as it entered the euro area in 2009, i.e., after applying the managed float system between 1998 and 2005, the SKK spent the following three years under the less flexible ERMII regime. A different approach can also be seen in the case of the CZK. In November 2013, the Czech central bank decided to use the exchange rate as a monetary policy instrument resulting in a move from a managed float system to a less flexible intervention system with a set floor at the level of EUR/CZK 27. Above the floor, the exchange rate is market-determined.

How the volatility of nominal exchange rates of CE currencies changes through different exchange rate regimes is shown in Table 8 below:

Table 8 | Volatilities of nominal exchange rates under different regimes

EUR/CZK		EUR/SKK		EUR/HUF		EUR/PLN	
ER regime	volatility	ER regime	volatility	ER regime	volatility	ER regime	volatility
03/03/1993–29/02/1996 basket peg, band +/-0.5%	0.371738 <i>Note: data available only from 02/08/1993</i>	14/07/1994–31/12/1995 basket peg, band +/-1.5%	Data not available	02/08/1991–15/03/1995 adjustable peg (irregular devaluations) band +/-0.3% –/+2.25%	Data not available	14/10/1991–05/03/1995 crawling peg, band +/- 0.6%	Data not available
01/03/1996–26/05/1997 basket peg, band +/-7.5%	0.570721	01/01/1996–30/07/1996 basket peg, band +/-3.0%	Data not available	16/03/1995–30/04/2001 crawling peg, band +/-2.25%	5.446530 <i>Note: data available only from 01/01/1999</i>	06/03/1995–15/05/1995 crawling peg, band +/- 2%	Data not available
27/05/1997–06/11/2013 managed float	4.377472	31/07/1996–31/12/1996 basket peg, band +/-5.0%	Data not available	01/05/2001–30/09/2001 crawling peg, band +/-15%	5.557278	16/05/1995–24/02/1998 crawling peg, band +/- 7%	Data not available
07/11/2013–present Intervention regime (floor set at around 27.0)	0.155208 <i>Note: time series ended on 31/12/2014</i>	01/01/1997–30/09/1998 basket peg, band +/-7.0%	Data not available	01/10/2001–25/2/2008 horizontal peg, 100% EUR, band +/-15%	8.821312	25/02/1998–11/04/2000 crawling peg, band +/- 15%	0.136005 <i>Note: data available only from 01/01/1999</i>
		01/10/1998–24/11/2005 managed float	1.892928 <i>Note: data available only from 01/01/1999</i>	26/02/2008–present free float	19.27760 <i>Note: time series ended on 31/12/2014</i>	12/04/2000–present free float	0.306803 <i>Note: time series ended on 31/12/2014</i>
		25/11/2005–31/12/2008 peg 100% EUR +/-15% (ERM II)	2.662918				
		01/01/2009 EMU	0.0				

Note: Volatility is measured as a standard deviation (based on daily figures).

Note: The EUR/CZK exchange rate before euro introduction was recalculated from DEM/CZK or the basket of respective former national currencies.

Source: Author's calculations based on data from the DataStream database

The results clearly confirm a very intuitive conclusion that the more flexible an exchange rate regime is, the more volatile the respective currency. This hypothesis is valid for all the currencies under investigation.

However, taking into account the mainstream view that nominal volatility does not have any impact in the long term, the question that arises is whether volatility of the real exchange rates is determined by the flexibility of the exchange rate system. Volatilities of respective real effective exchange rates of CE currencies under different exchange rate regimes are represented in Table 9 below:

Table 9 | Volatilities of real effective exchange rates under different regimes

CZK		SKK		HUF		PLN	
ER regime	volatility	ER regime	volatility	ER regime	volatility	ER regime	volatility
03/03/1993– 29/02/1996 basket peg, band +/-0.5%	1.925061	14/07/1994– 31/12/1995 basket peg, band +/-1.5%	0.616748	02/08/1991– 15/03/1995 adjustable peg (irregular devaluations) band +/-0.3% – +/-2.25%	2.035759 <i>* based on data from December 1992</i>	14/10/1991– 05/03/1995 crawling peg, band +/- 0.6%	1.789789 <i>* based on data from December 1992</i>
01/03/1996– 26/05/1997 basket peg, band +/-7.5%	1.816578	01/01/1996– 30/07/1996 basket peg, band +/-3.0%	0.315851	16/03/1995– 30/04/2001 crawling peg, band +/-2.25%	3.797941	06/03/1995– 15/05/1995 crawling peg, band +/- 2%	1.151535
27/05/1997– 06/11/2013 managed float	13.90059	31/07/1996– 31/12/1996 basket peg, band +/-5.0%	0.221420	01/05/2001– 30/09/2001 crawling peg, band +/-15%	1.353359	16/05/1995– 24/02/1998 crawling peg, band +/- 7%	3.184114
07/11/2013– present Intervention regime (floor set at around 27.0)	0.996485	01/01/1997– 30/09/1998 basket peg, band +/-7.0%	1.329397	01/10/2001– 25/2/2008 horizontal peg, 100% EUR, band +/-15%	6.002546	25/02/1998– 11/04/2000 crawling peg, band +/- 15%	2.836713
		01/10/1998– 24/11/2005 managed float	8.513663	26/02/2008– present free float	5.314608	12/04/2000– present free float	6.612350
		25/11/2005– 31/12/2008 peg 100% EUR +/-15% (ERM II)	7.362501				
		01/01/2009 EMU	1.779245				

Note: Volatility is measured as a standard deviation (based on monthly figures), effective exchange rates are taken from the OECD database.

Source: Author's calculations based on data from the DataStream database

Based on the results in Table 9, it is clear that exchange rate volatility increases with a more flexible exchange rate system not only in the case of nominal terms but also in real terms. Nevertheless, while nominal volatility is lower than real volatility in

a system of fixed or less flexible exchange rates, the opposite is true for flexible systems: exchange rate volatility is higher in nominal terms than in real terms. The reason behind this is the fact that in the free-float system, the reaction of the exchange rate to changes in demand/supply is immediate. On the contrary, consumer prices (used as a deflator for real exchange rate calculations) are more sticky than flexible.

Conclusion

The main goal of this paper was to investigate developments of exchange rate time series of Central European currencies and find evidence of some stylised facts.

First of all, we found that all the CE nominal exchange time series are not stationary, which is a confirmation of the convergence process in all the respective economies. This is even more pronounced in real terms. Turning to return time series, we confirmed the stationarity of all the series. However, normality was not proven, confirming the fat-tail distribution of exchange rate returns.

Volatility of exchange rates was investigated from several points of views. First of all, we found a time-changing volatility in all the series, i.e., heteroskedasticity was confirmed. We tried to model the volatility using GARCH models. The result is that the GARCH (1,1) model was the most suitable for modelling daily returns of all the CE currencies. We showed that the T-GARCH (1,1) model, taking asymmetry into account, is also possible for the EUR/HUF and EUR/PLN time series. However, better results were achieved using the E-GARCH (1,1) modelling approach.

Finally, we investigated the behaviour of nominal and real exchange rates under different exchange rate regimes in Central European countries. Our results confirmed that the more flexible an exchange rate regime is, the more volatile the respective currency is. This is true for both nominal and real exchange rates. We found that while nominal volatility is lower than real volatility in a system of fixed or less flexible exchange rates, the opposite is true for flexible systems: exchange rate volatility is higher in nominal terms than in real terms.

References

- ARLT, J. and ARLTOVÁ, M., 2001. Financial Time Series and Their Features. *Acta Oeconomica Pragensia*, 9(4), 7–20. ISSN 0572-3043.
- BOLLERSLEV, T., 1986. Generalized Autoregressive Conditional Heteroskedasticity. *Journal of Econometrics*, 31(3), 307–327. ISSN 0304-4076.
- BOLLERSLEV, T. and WOOLDRIDGE, J. M., 1992. Quasi-Maximum Likelihood Estimation and Inference in Dynamic Models with Time-Varying Covariances. *Econometric Reviews*, 11(2), 143–172.
- BUBÁK, V. and ŽIKEŠ, F., 2009. Distribution and dynamics of Central-European exchange rates: evidence from intraday data. *Finance a úvěr*, 59(4), 334–359. ISSN 0015-1920.
- DE GRAUWE, P. and KALTWASSER, P. R., 2012. The Exchange Rate in a Behavioral Finance Framework. In JAMES, J.; MARSH, I. W. and SARNO, L. *Handbook of Exchange Rates*. New Jersey: John Wiley & Sons. 111–132. ISBN 978-0-470-76883-9.
- DURČÁKOVÁ, J., 2011. Foreign Exchange Regimes and Foreign Exchange Markets. *Prague Economic Papers*, 20(4), 309–328. ISSN 1220-0455. DOI: 10.18267/j.pep.402

- ENDERS, W., 2010. *Applied Econometric Time Series* (3rd Edition). Wiley. ISBN 978-0-470-50539-7.
- ENGLE, R., 1982. Autoregressive Conditional Heteroscedasticity with Estimates of the Variance of United Kingdom Inflation. *Econometrica*, 50(4), 987–1007. ISSN 1468-0262.
- FIDRMUC, J. and HORVÁTH, R., 2008. Volatility of Exchange Rates in Selected EU New Members: Evidence from Daily Data. *Economic Systems*, 32(1), 103–118. ISSN 0939-3625.
- FIŠER, R. and HORVÁTH, R., 2010. Central Bank Communication and Exchange Rate Volatility: A GARCH Analysis. *Macroeconomics and Finance in Emerging Market Economies*, 3(1), 25–31. ISSN 1752-0843.
- FRÖMMEL, M., 2010. Volatility Regimes in Central and Eastern European Countries' Exchange Rates. *Czech Journal of Economics and Finance (Finance a úvěr)*, 60(1), 2–21. ISSN 0015-1920.
- GREEN, W. H., 2008. *Econometric Analysis* (6th International Edition). Pearson Education. ISBN 978-0135132456.
- HORVÁTH, R., 2005. Exchange Rate Variability, Pressures and Optimum Currency Area Criteria: Implications for Central and Eastern European Countries [Czech National Bank Working Paper Series, No. 8/2005, online]. [accessed June 5, 2015]. Available at: http://www.cnb.cz/en/research/research_publications/cnb_wp/download/cnbwp_2005_08.pdf
- JAMES, J.; MARSH, I. and SARNO, L., 2012. *Handbook of Exchange Rates*. New Jersey: John Wiley & Sons. ISBN 978-0-470-76883-9.
- KOČENDA, E. and VALACHY, J. 2006. Exchange rate volatility and regime change: Visegrad comparison. *Journal of Comparative Economics*, 34(4), 727–753. ISSN 0147-5967.
- LOTHIAN, J. R., 1998. Some new stylized facts of floating exchange rates. *Journal of International Money and Finance*, 17(1998), 29–39. ISSN 0261-5606.
- MANDELBROT, B., 1963. The variation of certain speculative prices. *The Journal of Business*, 36(4), 394–419. ISSN 00219398.
- MUSSA, M., 1986. Nominal exchange rate regimes and the behavior of real exchange rates: Evidence and implications. *Carnegie-Rochester Conferences on Public Policy Series*, 25(Autumn 1986), 117–214. DOI: 10.1016/0167-2231(86)90039-4
- TAYLOR, S., 1986. *Modelling financial time series*. New York: Wiley. ISBN 978-0471909934.
- SEWELL, M., 2011. Characterization of financial time series [Research Note RN/11/01, online]. University College London. [accessed June 10, 2015]. Available at: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.378.6859&rep=rep1&type=pdf>