Price risk and bid-ask spreads of currency options

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Received: 21st December, 2005

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Practical applications

The findings of this study suggest that currency options dealers, when determining the bid-ask spread of a currency option, need to perform a regression analysis with the bid-ask spreads of a currency option as the dependent variable and all the Greeks of the option in question as independent variables. Even though this study found the effects of delta (positive) and gamma (negative) are most pronounced, the study also found that the bid-ask spread of a currency option is affected by other Greeks including vega, rho and theta.

Abstract

This paper investigates the spread of bid and ask prices of currency options quoted by Philadelphia Stock Exchange (PHLX) currency option specialists. Following H. Bessembinder ('bid-ask Spreads in the Interbank Foreign Exchange Markets', Journal of Financial Economics, Vol. 35, pp. 317-348, 1994), this paper suggests that the bid-ask spread for currency

options can be attributable to inventory cost. Nonetheless, delta and gamma, among other price risk measures, are found to be the most significant explanatory variables in the bid-ask spread of currency options. Existing studies have shown that the bid-ask spreads of equity options increase with delta and gamma. This study finds that the bid-ask spread of currency options increases with delta, consistent with the existing

studies on equity options. It is found, however, that the bid–ask spread decreases with gamma, in contrast to other studies.

INTRODUCTION

In market microstructure literature, the bid–ask spread is made up of three components: order processing costs, inventory holding costs and asymmetric information costs. The order processing component, or cost of dealer processing, represents a fee charged by market makers for standing ready to match buy and sell orders.¹ Inventory holding costs compensate dealers for the risk of holding undiversified portfolios. Models of inventory holding costs focus on how risk-averse dealers adjust prices to control their asset inventory.² Expectations are that the bid–ask spread is positively related to price, and the volatility of the security and negatively related to trading volume. Finally, the asymmetric information costs component is to compensate market makers who sustain losses from trading with informed traders.³ Information-based models consider learning and adverse selection problems when some market participants have private information.⁴

The bid–ask spread and its three components have been widely analysed using stock market, foreign exchange market and stock option market data, but not using data on currency options. Empirical microstructure studies using foreign exchange have been limited until recently owing to the lack of transaction level data; to the authors' knowledge, no researcher has studied which price risk

measures are most significant when explaining the bid–ask spreads of foreign currency options.⁵

The purpose of this paper is to estimate empirically the effects of the price risk measures of currency options on the bid–ask spreads of currency options traded on the Philadelphia Stock Exchange (PHLX). Infrequent trading of currency options at the PHLX increases the price risk of the unwanted inventory held by the PHLX currency options specialists.⁶ For this reason, the paper postulates that the quoted bid–ask spread of foreign currencies options is mainly attributable to inventory costs.⁷ Given that inventory costs arise from the price risk of the specialist's inventories and that the price risk of currency options is derived mainly from the price risk of the underlying currency, one can further assume that the price risk of the specialist's currency options inventory (inventory costs) also arises from the exchange rate uncertainty of the underlying currency. It may also depend, however, on the volatility of the underlying currency value, interest rate fluctuations or changing maturity of the option.

The price risks of currency options are calculated in this paper, based on the Garman and Kohlhagen foreign currency European option- pricing formula adapted for American options traded in PHLX.⁸ They include: delta and gamma from spot exchange rate changes of the underlying foreign currency, vega from changes in the volatility of exchange rate, rho from changes in domestic and foreign riskless interest rates, and theta from shortening maturity of options (time value erosion).

PRICE RISK MEASURES OF CURRENCY OPTIONS AND BID-ASK SPREAD

The Garman-Kohlhagen formula and price risk measures

Price risk measures are calculated using the Garman-Kohlhagen formula for European options, which is modified for American options.⁹ The Garman-Kohlhagen formula treats the foreign interest rate as a continuous dividend yield. For European calls and puts, the formulae are

$$\begin{aligned} c &= Se^{-r_f\tau}N(d_1) - Xe^{-r\tau}N(d_2) \\ p &= -Se^{-r_f\tau}N(-d_1) + Xe^{-r\tau}N(-d_2) \end{aligned} \quad (1)$$

where S is the spot exchange rate for the underlying currency (the dollar value of one unit of the underlying currency), r is the riskless interest rate for the dollar, r_f is the riskless interest rate for the underlying currency, τ is the time to maturity, X is the exercise price, $N(\cdot)$ is the cumulative normal density function, and

$$\begin{aligned} d_1 &= \frac{\ln(S/X) + (r - r_f + \sigma^2/2)\tau}{\sigma\sqrt{\tau}} \\ d_2 &= d_1 - \sigma\sqrt{\tau} \end{aligned} \quad (2)$$

where σ is the volatility of the spot exchange rate for the underlying currency.

Signs of price risk measures¹⁰ of foreign currency options are

$$\begin{aligned} \Delta_{\text{call}} &= \frac{\partial c}{\partial S} > 0, & \Delta_{\text{put}} &= \frac{\partial p}{\partial S} < 0 \\ \Gamma_{\text{call}} &= \frac{\partial^2 c}{\partial S^2} > 0, & \Gamma_{\text{put}} &= \frac{\partial^2 p}{\partial S^2} \\ & & &= \Gamma_{\text{call}} > 0 \end{aligned}$$

$$\text{Vega}_{\text{call}} = \frac{\partial c}{\partial \sigma} > 0, \quad \text{Vega}_{\text{put}} = \frac{\partial p}{\partial \sigma} > 0$$

$$\text{Rho}_{\text{call}} = \frac{\partial c}{\partial r} > 0, \quad \text{Rho}_{\text{put}} = \frac{\partial p}{\partial r} < 0$$

$$\text{RhoF}_{\text{call}} = \frac{\partial c}{\partial r_f} < 0, \quad \text{RhoF}_{\text{put}} = \frac{\partial p}{\partial r_f} > 0$$

$$\begin{aligned} \text{Theta}_{\text{call}} &= -\frac{\partial c}{\partial \tau} = ?, & \text{Theta}_{\text{put}} &= \\ & & & -\frac{\partial p}{\partial \tau} < 0^{11,12} \end{aligned}$$

Relation between bid-ask spread of currency options and price risk measures

The bid-ask spread of currency options can be attributed mostly to inventory costs. Currency options specialists, who often have to accommodate transitory order imbalance, must carry unwanted inventories. Dealers can control inventory levels to a certain degree by lowering the bid and ask quotes when the inventory level exceeds an optimal level and raising price quotes when inventory level is below an optimal level. Since currency options in PHLX are traded infrequently, however, PHLX specialists are likely to hold an undesirable level of inventories longer. Transactions data used in this study include the four most frequently traded currency options in PHLX during 1996: British pound (BP), Deutsche mark (DM), Japanese yen (JY) and Swiss franc (SF).¹³ The sensitivities of bid-ask spread were examined with respect to measures of price risk of call and put options, respectively, on each currency in the following regression equations

$$\begin{aligned} \text{bid-ask spread}_{\text{call},i} &= a_0 + a_1 \Delta_{\text{call},i} \\ &+ a_2 \Gamma_{\text{call},i} + a_3 \text{Vega}_{\text{call},i} + a_4 \text{Rho}_{\text{call},i} \\ &+ a_5 \text{RhoF}_{\text{call},i} + a_6 \text{Theta}_{\text{call},i} + \varepsilon_{\text{call},i} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{bid-ask spread}_{\text{put},i} = & b_0 + b_1 \text{Delta}_{\text{put},i} \\ & + b_3 \text{Vega}_{\text{put},i} + b_4 \text{Rho}_{\text{put},i} + b_5 \text{Rho}F_{\text{put},i} \\ & + b_6 \text{Theta}_{\text{put},i} + \varepsilon_{\text{put},i} \end{aligned} \quad (4)$$

where $i = \text{BP, DM, JY, SF}$

Delta measures the sensitivity of the price of option to the price of the underlying asset. For a call option, the larger the delta (which is positive), the larger the change in the option price for a small change in the underlying spot exchange rate, thereby indicating the higher price risk of the call option. Hence, the specialist sets a wider bid-ask spread for a call option with the larger delta, ie $a_1 > 0$. For a put option, a larger delta (which is negative) indicates a flatter slope of the put option price. Hence, the larger the delta of the put, the smaller the impact of the spot exchange rate change on the put price and, consequently, specialists set a narrower spread, ie $b_1 < 0$.

Delta accurately predicts how much the option price would change for a *small* change in the underlying exchange rate. Delta, however, becomes a less accurate predictor of option price change for a *large* exchange rate change, because of the convexity of option prices. For a large exchange rate increase (decrease), delta underpredicts (overpredicts) the increase (decrease) in the call option price, while it overpredicts (underpredicts) the decrease (increase) in the put option price.

Gamma measures convexity of options. Jameson and Wilhelm¹⁴ and De Fontnouvelle *et al.*¹⁵ argue that the gamma of an option positively affects the bid-ask spreads, because a larger gamma requires more frequent rebalancing of a delta hedged portfolio. The empirical results of

the two studies are somewhat mixed:

Jameson and Wilhelm show positive effects of gamma on the bid-ask spread, while De Fontnouvelle *et al.* show positive as well as negative results. De Fontnouvelle *et al.*

estimated ten equations for both put and call options in five option classes. While five equations show positive coefficients for gamma, with one significant and four insignificant cases, five other equations have the 'wrong sign', with two significant and three insignificant cases.

There is another effect of gamma on a delta hedged portfolio that works in favour of a dealer, indicating a negative effect of gamma on the bid-ask spread of an option. Merton has shown that an intermediary with a positive gamma of a delta hedged portfolio will gain with a large change, up or down, in the price of the underlying asset.¹⁶ Therefore, when a specialist fills a sell order resulting in a long position in an option, convexity of (call or put) option price is a desirable feature. The specialist is then willing to quote a higher bid price for a high gamma option than for a low gamma option. When the specialist fills a buy order resulting in a short position, however, it is an undesirable feature. In this situation, the specialist is willing to quote a lower ask price for a high gamma option than for a low gamma option. One can therefore expect that a larger gamma results in a smaller bid-ask spread, ie $a_2 < 0$ and $b_2 < 0$. It is possible that the effect of gamma on bid-ask spread may be insignificant or even positive if the costs of rebalancing a hedged portfolio with a non-zero gamma exceed the benefits of the gamma on the value of a dealer's position.

Vega measures how much the option price will change when the volatility of exchange rate changes. Black–Scholes and the Garman–Kohlhagen formula, however, assume constant volatility.¹⁷ In order to examine the effect of exchange rate volatility changes on option prices within the framework of the Garman–Kohlhagen model, it is assumed that the volatility at the time of option trading is expected to remain constant over the life of options. Thus, the larger the vega, the larger the impact of changes in exchange rate volatility on the option price. Hence, one expects the larger vega to result in a larger bid–ask spread, ie $a_3 > 0$ and $b_3 > 0$. This is consistent with conclusions of earlier studies on portfolio rebalancing cost, where portfolio rebalancing cost is shown to be proportional to vega.¹⁸ Jameson and Wilhelm¹⁴ also examine the effects of the uncertainty in volatility that cannot be hedged on stock option spreads, and they find that both variables explain the statistical significance of the option spread.

Currency option value also depends on both domestic and foreign interest rates. Changes in domestic or foreign interest rate almost immediately affect the exchange rate. The indirect effect of interest rate changes on the option value through exchange rate changes is already captured in delta and gamma. The rho corresponding to the domestic interest rate (Rho) only measures the direct effect of interest rate changes on currency option value; that is, it measures the sensitivity of option value to the domestic interest rate. The price of currency call (put) options increases (decreases) with domestic interest rate.

When the domestic interest rate increases, the present value of the exercise price that call (put) option holders pay (receive) upon exercising the option decreases, thereby increasing (decreasing) the value of currency calls (puts). Therefore, the rho corresponding to the domestic interest rate is positive for calls and negative for puts. The larger the rho corresponding to the domestic interest rate, the larger (smaller) the impact of domestic interest rate changes on the price of calls (puts). Hence, one expects the larger rho corresponding to the domestic interest rate to result in a larger (smaller) bid–ask spread for calls (puts), ie $a_4 > 0$ and $b_4 < 0$.

The price of currency call (put) options decreases (increases) with foreign interest rate. When foreign interest rate increases, holding exchange rate constant, the value of foreign currency, not including interest payment, decreases, thereby decreasing (increasing) the value of currency calls (puts). The rho corresponding to the foreign interest rate (RhoF) is negative for calls and positive for puts. It measures the sensitivity of option value to changes in the foreign interest rate. The larger the rho corresponding to the foreign interest rate, the smaller (larger) the impact of foreign interest rate changes on the price of calls (puts). Thus, one expect the larger rho corresponding to the domestic interest rate to result in a smaller (larger) bid–ask spread for calls (puts), ie $a_5 < 0$ and $b_5 > 0$.

Finally, the price of currency options depends on the maturity of options. Theta measures the time value erosion. As the time to maturity decreases, the option becomes less valuable. The more negative

the theta, the larger the value loss of options with the passage of time. The specialist will prefer options with a lower rate of time value erosion, ie a larger (and hence smaller absolute value) theta. Therefore, an option with a larger theta is probably quoted at a higher bid and a higher ask compared with an option with a lower theta. The effect of theta on bid–ask spread is not clear, however, ie signs of a_6 and b_6 are ambiguous.

DESCRIPTION OF DATA

Transactions data for currency options are obtained from the currency pricing history tape of the PHLX. The tape has most of the transactions data for all the currency options traded at the PHLX from 3rd January, 1984, to 30th May, 1997.¹⁹ Each line representing a transaction reports: a ticker symbol, the trade date, transaction time, expiration month, strike price, put or call, option premium, bid, ask, and concurrent Telerate quotes for spot, bid and ask exchange rate. About 1.6 million trades are recorded on the tape for the entire period.

To reduce the computational requirement, only one-year data are selected for empirical estimation. The transaction data for the calendar year 1996 is selected because it is the latest period for which trade data are available. There are a total of 78 ticker symbols in the 1996 dataset, with 2,232,802 contracts traded in 57,857 transactions within 254 trading days.²⁰ The data are further restricted to the four most frequently traded American currency options and the corresponding European options. The selected ticker symbols are: British pounds

(XBP/CBP), Deutsche mark (XDM/CDM), Japanese yen (XJY/CJY) and Swiss franc (XSF/CSF). These are the regular options expiring on the Friday before the third Wednesday of the expiration month. The data for the selected eight ticker symbols in 1996 show a total of 1,120,043 contracts traded in 35,158 transactions within 254 trading days (see Table 1).

The selected dataset is cleaned up by eliminating the following incomplete records: (i) records with missing spot exchange rates; (ii) records with missing bid or ask price for options; (iii) records with missing exercise prices; (iv) records with option premium outside the bid–ask quotes, ie option premium higher than asked price, or lower than bid price; (v) records with quoted bid–ask spread greater than maximum permitted;²¹ and (vi) duplicate records. There are a total of 27,574 usable currency options records.

The interest rates used are from Datastream. They are the daily quotes of the British Bankers Association London interbank settlement fixing rates (BBAISR) for maturities ranging from one month to 12 months for all four currencies and the US dollar.

The values for delta, gamma, vega, Rho, Rhof and theta are calculated using the Garman–Kohlhagen formula for European options and a recursive integration method by modifying the Garman–Kohlhagen formulae for American options.²² The exchange rate volatility of a currency on a given date is assumed to be the average implied volatility computed from the currency options traded on the immediately preceding date. The currency options used

Table 1: 1996 Transactions for the eight ticker symbols^a

<i>Symbol</i>	<i>Contract volume</i>	<i>No. of records</i>	<i>Daily average transaction frequency</i>
XJY (Yen, American)	209,556	7,242	28.5
XDM (DM, American)	351,541	7,032	27.7
XSF (SF, American)	102,462	6,385	25.1
CSF (SF, European)	111,443	5,502	21.7
XBP (BP, American)	248,130	4,912	19.3
CJY (Yen, European)	41,920	1,672	6.6
CDM (DM, European)	37,843	1,321	5.2
CBP (BP, European)	17,148	1,092	4.3
Total for 8 ticker symbols in 1996	1,120,043	35,158	138.4
Total for all 78 ticker symbols in 1996	2,232,802	57,857	227.8

^aThe selected ticker symbols are: British pounds (XBP/CBP), Deutsche Mark (XDM/CDM), Japanese Yen (XJY/CJY) and Swiss Franc (XSF/CSF). These are the regular options expiring on Friday before the third Wednesday of the expiration month. The data for the selected 8 ticker symbols in 1996 show a total of 1,120,043 contracts traded in 35,158 transactions within 254 trading days.

to calculate the implied volatility were restricted to the options near-at-the-money, with strike prices within 10 per cent of the spot prices and maturity longer than one week.

Two records were deleted from the sample owing to computational non-convergence, leaving a total of 27,572 records for regression analysis.

REGRESSION RESULTS

The regression results for bid-ask spread of call options, Equation (3), are in Tables 2 and 3. The regression results for bid-ask spread of put options, Equation (4), are in Tables 4 and 5.

The constant term is highly significant in all the equations. The results for delta,

gamma and vega are highly significant at the less than 0.1 per cent significance level. Delta is highly significant in all the equations with positive coefficients for call options and negative for put options, as expected.

Gamma is *negative* in all the equations, consistent with the positive benefits of an option's convexity to a dealer holding a delta hedged portfolio, and significant in all but one equation, yen (JY) call options (significant at 7.2 per cent). It should be noted that the negative effect of gamma in this study is contrary to the empirical findings in equity options by Jameson and Wilhelm,¹⁴ but not inconsistent with the findings of De Fontnouvelle *et al.*¹⁵

Vega is significant at or less than 0.1 per

Table 2: Regression equations for bid-ask spreads in 1996 call trades^a

	Equation for BP call		Equation for DM call		Equation for JY call		Equation for SF call	
	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat	Coefficient	t-stat
Const	1.55E-03	27.09	3.22E-04	43.79	4.92E-06	24.08	3.13E-04	31.25
Delta	6.06E-04	8.41	3.15E-04	29.22	4.90E-06	10.94	3.31E-04	23.79
Gamma	-2.36E-05	-7.98	-1.80E-06	-5.64	-2.34E-10	-1.80	-6.29E-06	-11.61
Rho	-2.76E-02	-6.69	-4.90E-03	-1.78	9.77E-03	2.18	2.44E-03	1.67
RhoF	-2.74E-02	-7.10	-4.12E-03	-1.65	8.96E-03	2.19	2.62E-03	2.00
Vega	-1.41E-03	-6.67	1.66E-03	14.10	6.40E-04	3.09	1.19E-03	13.27
Theta	-1.05E-04	-0.23	1.99E-04	0.98	5.31E-04	1.19	-9.28E-04	-5.68

^aRegression results for bid-ask spread of call options using the following equation

$$bid\text{-}ask\ spread_{call,i} = a_0 + a_1\Delta_{call,i} + a_2\Gamma_{call,i} + a_3V_{call,i} + a_4R_{call,i} + a_5RhoF_{call,i} + a_6\Theta_{call,i} + \varepsilon_{call,i}$$

The variable delta predicts how much option price would change for a small change in the underlying exchange rate while Gamma measures convexity of options. Rho and RhoF measures the sensitivity of option value to the domestic interest rate and the sensitivity of option value to changes in the foreign interest rate, respectively. Vega measures how much option price will change when the volatility of exchange rate changes and Theta measures the time value erosion.

Table 3: Regression statistics — call trades

	BP call	DM call	JY call	SF call
NOB	1,949	3,126	2,312	5,003
Y-mean	1.48E-03	5.24E-04	7.61E-06	5.61E-04
Y-sdt	6.54E-04	1.46E-04	2.80E-06	1.69E-04
SSR	5.93E-04	3.81E-05	1.39E-08	1.02E-04
Var of res.	3.05E-07	1.22E-08	6.01E-12	2.05E-08
SER	5.53E-04	1.11E-04	2.45E-06	1.43E-04
R ²	0.2882	0.4258	0.2365	0.2820
R ² -adj	0.2860	0.4247	0.2345	0.2812
F-stat	1.31E+02	3.86E+02	1.19E+02	3.27E+02
LLF	1.19E+04	2.40E+04	2.66E+04	3.72E+04

cent for all the equations. The signs are positive as expected for all, except for British pound (BP) call and BP put. The

negative sign (and significant at less than 0.1 per cent) for vega in BP equations for call and put cannot be explained.²³ Theta,

Table 4: Regression equations for bid-ask spreads in 1996 put trades^a

	<i>Equation for BP put</i>		<i>Equation for DM put</i>		<i>Equation for JY put</i>		<i>Equation for SF put</i>	
	<i>Coefficient</i>	<i>t-stat</i>	<i>Coefficient</i>	<i>t-stat</i>	<i>Coefficient</i>	<i>t-stat</i>	<i>Coefficient</i>	<i>t-stat</i>
Const	1.43E-03	39.77	3.48E-04	34.83	4.81E-06	25.73	3.38E-04	37.01
Delta	-2.54E-04	-4.87	-3.04E-04	-27.70	-5.50E-06	-21.41	-3.15E-04	-28.06
Gamma	-1.26E-05	-5.54	-1.83E-06	-6.66	-7.56E-10	-7.91	-4.10E-06	-8.05
Rho	-3.74E-03	-9.77	-3.07E-04	-4.89	4.31E-05	0.36	6.99E-05	0.72
RhoF	-3.82E-04	-6.99	-7.94E-05	-4.17	-1.85E-04	-6.61	-1.26E-07	-0.01
Vega	-1.59E-03	-6.86	5.08E-04	6.82	1.17E-03	11.86	8.38E-04	11.38
Theta	2.42E-04	0.64	3.63E-04	2.19	-1.09E-03	-3.31	-5.99E-04	-3.60

^aSee footnote to Table 3.

Table 5: Regression statistics — put trades

	<i>BP call</i>	<i>DM call</i>	<i>JY call</i>	<i>SF call</i>
NOB	2,690	4,302	2,782	5,408
Y-mean	1.31E-03	5.19E-04	8.16E-06	5.54E-04
Y-sdt	5.37E-04	1.45E-04	2.80E-06	1.66E-04
SSR	6.93E-04	5.96E-05	1.56E-08	1.12E-04
Var of res.	2.58E-07	1.39E-08	5.63E-12	2.07E-08
SER	5.08E-04	1.18E-04	2.37E-06	1.44E-04
R ²	0.1057	0.3439	0.2817	0.2483
R ² -adj	0.1037	0.3430	0.2802	0.2475
F-stat	5.28E+01	3.75E+02	1.81E+02	2.97E+02
LLF	1.66E+04	3.28E+04	3.21E+04	4.02E+04

Rho and Rhof have mixed results in significance and in signs.

In summary, the empirical results support the hypothesis that the bid-ask spread of currency options increases with the absolute value of delta and decreases with gamma for all currency options. The bid-ask spread

is found to be positively related to vega for call and put options on Deutsche mark (DM), Japanese yen (JY) and Swiss franc (SF) and negatively for call and put on British pound (BP). The effects of all other Greek letters, theta, Rho, and RhoF, are mixed in significance and sign.

CONCLUSION

The determinants of the spread of bid and ask prices of currency options are examined in this paper using the PHLX currency option data.

Foreign currency markets are driven primarily by macroeconomic information; bid–ask spread of currencies can be attributed mainly to inventory costs and, thus, bid–ask spread of options of foreign currencies as well. Prior studies have demonstrated that the price risk of the specialist's currency option inventory (inventory costs) can be best explained by the price risk of the currency options. This study shows that the bid–ask spreads can be mostly explained by two measures of price risk, delta and gamma, which are due to the uncertainty of the underlying exchange rates. The most significant empirical finding is that the bid–ask spread increases with the absolute value of delta and *decreases* with gamma, indicating that the uncertainty in the underlying currency value is the most significant determinant of the bid–ask spread of currency options. The finding that the bid–ask spread *decreases* with gamma is in contrast to earlier studies on equity options market.

The study also finds that other price risk measures such as vega, which is due to changes in the volatility of the exchange rate, Rho, which is due to changes in the domestic interest rate, and theta, which is due to different terms of the options, are also significantly related to the bid–ask spreads for many currency options.

References and Notes

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- 5 Several authors make a significant contribution to the literature by providing models that not only show the proportional relationship between exchange rate volatility and bid–ask spreads but also predict the change in volume and volatility at the opening and closing of the trading day and determine how liquidity traders affects price efficiency. See, for example: Glassman, D. (1987) 'Exchange Rate Risk and Transaction Costs: Evidence from bid–ask Spreads', *Journal of International Money and Finance*, Vol. 6, No. 4,

- pp. 479–490; Admati and Pfleiderer, ref. 2 above; and Subrahmanyam, A. (1991) ‘Risk Aversion, Market Liquidity, and Price Efficiency’, *Review of Financial Studies*, Vol. 4, No. 3, pp. 417–441.
- 6 For example, it was not uncommon to observe that for more than two hours there were no trades of options on British pound, which was one of most frequently traded currency options in PHLX during 1996.
 - 7 See Bessembinder, H. (1994) ‘bid–ask Spreads in the Interbank Foreign Exchange Markets’, *Journal of Financial Economics*, Vol. 35, pp. 317–348.
 - 8 Note that the intent of this paper is to calculate the price risk of currency options and determine which of the price risk measure(s) is (are) most significant, even though other studies have focused on the spread of the underlying assets and option price and volume. See Garman, M. and Kohlhagen, S. (1983) ‘Foreign Currency Option Values’, *Journal of International Money and Finance*, Vol. 2, No. 3, pp. 231–238.
 - 9 The majority of the PHLX currency options are American options. For numerical computations of American options, a recursive integration method is used to modify the Garman–Kohlhagen formulae. For the recursive integration method, see Huang, J., Subrahmanyam, M. G. and Yu, G. G. (1996) ‘Pricing and Hedging American Options: A Recursive Integration Method’, *Review of Financial Studies*, Vol. 9, No. 1, pp. 277–300.
 - 10 Theta is not a risk measure because there is no uncertainty in the passage of time, but it measures the time value erosion of an inventory of currency options.
 - 11 Detailed expressions of Greek symbols can be found in most options text books.
 - 12 Gammas for both European call and put are positive and have the same expression. The sign of theta for European call currency option is usually negative except in-the-money European call on a currency with a very high interest rate.
 - 13 The dataset obtained from PHLX covers the period from January 1984 to May 1997. The year 1996 was selected for empirical test, because it was the last year with a full year’s data.
 - 14 Jameson, M. and Wilhelm, W. (1992) ‘Market Making in the Options Markets and the Costs of Discrete Hedge Rebalancing’, *Journal of Finance*, Vol. 43, No. 2, pp. 765–779.
 - 15 De Fontnouvelle, P., Fishe, R. P. H. and Harris, J. H. (2003) ‘The Behavior of bid–ask Spreads and Volume in Options Markets during the Competition for Listings in 1999’, *Journal of Finance*, Vol. 58, No. 6, pp. 2437–2463.
 - 16 See Merton, R. C. (1990) ‘Continuous–Time Finance’, revised edn, Blackwell, Cambridge, MA, p. 455.
 - 17 See Black, F. and Scholes, M. (1973) ‘The Pricing of Options and Corporate Liabilities’, *Journal of Political Economy*, Vol. 81, pp. 637–659; and Garman and Kohlhagen, ref. 8 above.
 - 18 See, for example, Leland, H. (1985) ‘Option Pricing and Replication with Transactions Costs’, *Journal of Finance*, Vol. 40, No. 5, pp. 1283–1301; Merton, ref. 16 above, Section 14.2; Boyle, P. P. and Vorst, T. (1992) ‘Option Replication in Discrete Time with Transaction Cost’, *Journal of Finance*, Vol. 47, No. 1, pp. 271–293; and Kaul, G., Nimalendran, M. and Zhang, D. (2003) ‘Informed Trading and Option Spreads’, Working Paper, University of South Carolina.
 - 19 There are two missing periods in 1985: 25th January–21st February and 25th October–26th November.
 - 20 The 78 symbols are: ADW, AZW, BPU, BPW, CAD, CAZ, CBP, CBX, CBY, CBZ, CCD, CCV, CDM, CDW, CDZ, CFF, CFV, CJV, CJY, CJZ, CSE, CSY, CSZ, DMW, DMZ, EAW, ECD, ECU, ECW, EDA, EDM, EDZ, EFF, EJY, EJZ, EPO, ESU, ESW, ESZ, FFW, JYW, JYZ, MXZ, MYW, MYX, MYZ, PMW, PMX, SFW, SFZ, XAD, XAZ, XBP, XBX, XBY, XBZ, XCD, XCV, XDA, XDB, XDC, XDD, XDE, XDM.
 - 21 Refer to the ‘Study Guide for Philadelphia Stock Exchange Foreign Currency Option Participants for the PHLX FCO Qualification Examination for Specialists, Registered Option Traders and Floor Brokers’.
 - 22 The numerical calculations are based on four-point Richardson extrapolation with geometric sequence, power of time-interval squared, exercisable once, twice, quadruple and octuple. This method improves computational accuracy severalfold over the arithmetic sequence method. The computational details are not included here, but are available from the authors upon request. See Garman and Kohlhagen, ref. 8 above, and Huang *et al.* ref. 9 above.
 - 23 One possible explanation is that vega may be related to volume for the BP. If the volatility of BP were to jump up, there may be more demand for options for the purpose of hedging activities. In this case, specialists who anticipate that inventory holding period will be short may not be as concerned about an increase in price risk of options as before.