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Citation for published version (APA):

Pelsser, A. (2003). Mathematical foundation of convexity correction. *Quantitative Finance*, *3*(1), 59-65.
https://doi.org/10.1088/1469-7688/3/1/306

Document status and date:
Published: 01/02/2003

DOI:
10.1088/1469-7688/3/1/306

Document Version:
Publisher's PDF, also known as Version of record

Document license:
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QUANTITATIVE FINANCE VOLUME 3 (2003) 59–65
INSTITUTE OF PHYSICS PUBLISHING

RESEARCH PAPER
quant.iop.org

Mathematical foundation of convexity correction

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Received 9 October 2002, in final form 26 December 2002
Published 4 February 2003
Online at stacks.iop.org/Quant/3/59

Abstract

A broad class of exotic interest rate derivatives can be valued simply by adjusting the forward interest rate. This adjustment is known in the market as *convexity correction.* Various *ad hoc* rules are used to calculate the convexity correction for different products, many of them mutually inconsistent. In this research paper we put convexity correction on a firm mathematical basis by showing that it can be interpreted as the side-effect of a change of probability measure. This provides us with a theoretically consistent framework to calculate convexity corrections. Using this framework we review various expressions for LIBOR in arrears and diff swaps that have been derived in the literature. Furthermore, we propose a simple method to calculate analytical approximations for general instances of convexity correction.

1. Introduction

Many products that are actively traded in interest rate derivative markets have pay-offs that only depend on a few interest rates which are only observed at one point in time. One could characterize such products as 'exotic European' options. The value of these products is determined solely by the (joint) probability distribution of the relevant rates at this one point in time. This explains why this type of product has become particularly liquid in recent years. Examples of this type of product are LIBOR in arrears swaps, diff swaps and constant maturity swaps (also known as CMS swaps) and CMS caps.

All these products can be characterized by the fact that certain interest rates are paid at the 'wrong' time and/or in the 'wrong' currency. It turns out that the price of these products can be expressed as the discounted forward rate, where the forward interest rate has to be adjusted to reflect the 'incorrect' payment. This adjustment is known in the market as *convexity correction* or *convexity adjustment.*

Practitioners use various *ad hoc* rules to calculate convexity corrections for different products, often based on Taylor approximations (see, for example, Brotherton-Ratcliffe and Iben 1993, Li and Raghavan 1996, Hunt and Pelsser 1998, Benhamou 2000). For an overview of applications to various products, see Hull (2000), chapters 19 and 20. However, many of these rules are theoretically inconsistent and cannot be used to derive convexity corrections for general products.

In this research paper, we will put convexity correction on a firm mathematical basis by showing that it can be interpreted as the side-effect of a change of numeraire. This means that we will show how convexity correction can be understood mathematically as the expected value of an interest rate under a different probability measure than its own martingale measure. In this setting we derive an exact expression for LIBOR in arrears[2]. To analyse convexity correction across different

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[2] Many of the single-currency results for LIBOR in arrears we review in this paper have also been derived by Jamshidian (1997), Rutkowski (1998) and Pugachevsky (2001). Pugachevsky also derives expressions for CMS rates, but he uses a different approximation than is proposed in this paper.

1469-7688/03/010059+07$30.00 © 2003 IOP Publishing Ltd PII: S1469-7688(03)58108-8

currencies, we show how the change of numeraire theorem can be applied to a multi-currency setting. In this setting we derive an exact expression for diff swaps[3]. Finally, we show how convexity corrections for general interest rate derivatives can be calculated analytically using the surprisingly simple but effective linear swap rate model (LSM) of Hunt and Kennedy (2000).

The remainder of this paper is organized as follows. In section 2 we show how the change of numeraire theorem can be extended to a multi-currency setting. In sections 3 and 4, we derive the theoretical framework to calculate convexity corrections for single- and multi-currency products. Finally, we show in sections 5 and 6 how convexity corrections for general interest rate payments and options on interest rate payments can be calculated using the approximation we propose.

2. Multi-currency change of numeraire theorem

In this section we review how, in an arbitrage-free economy, different probability measures can be used to value a given product. From this observation one can derive the well known change of numeraire theorem. Then we demonstrate how this theorem can be applied to multi-currency economies. With these tools we are then in a position to put the concept of convexity correction on a firm mathematical basis.

The well known change of numeraire theorem due to Géman *et al* (1995) shows how in an arbitrage-free economy an expectation under a probability measure Q^N generated by a numeraire N can be represented as an expectation under an equivalent (absolutely continuous) probability measure Q^M generated by the numeraire M times the Radon–Nikodym derivative $\mathrm{d}Q^N/\mathrm{d}Q^M$ which is equal to the ratio of the numeraires N/M. For an expectation at time 0 of a random variable $H(T)$ at time T we have

$$E^N(H(T)) = E^M\left(H(T)\frac{N(T)/N(0)}{M(T)/M(0)}\right), \tag{1}$$

where E^N, E^M denote expectations under the probability measures Q^N, Q^M respectively.

Many of the products we are interested in will be multi-currency products. Hence, we demonstrate in this section how the change of numeraire theorem can be applied to multi-currency economies. Suppose we have a domestic economy d and a foreign economy f together with the exchange rate $X^{(d/f)}(t)$ that expresses the value at time t of one unit of foreign currency in terms of domestic currency. This immediately implies the relation $X^{(f/d)} = 1/X^{(d/f)}$. We also assume that this system of economies and exchange rates is arbitrage free and complete. This implies that for a numeraire $N^{(d)}$ in the domestic economy there exists a unique martingale measure $Q^{N,d}$ such that all $N^{(d)}$ rebased traded assets in the domestic economy become martingales. Note that we have two types of traded asset in the domestic economy: the domestic assets $Z^{(d)}$ and the foreign assets denominated in domestic currency which are given by $X^{(d/f)}Z^{(f)}$. All these assets are traded assets in the domestic economy and can be used as numeraires if their values are strictly positive.

Let us now consider two numeraires, one in the domestic economy, say $N^{(d)}$, and one in the foreign economy, say $M^{(f)}$. As the exchange rate is strictly positive, the domestic value of the foreign numeraire $X^{(d/f)}M^{(f)}$ is a valid numeraire in the domestic economy. Hence, there exists a unique martingale measure $Q^{XM,d}$ such that all $X^{(d/f)}M^{(f)}$ rebased traded assets in the domestic economy become martingales. What is the relation between the probability measure $Q^{XM,d}$ in the domestic economy and $Q^{M,f}$ in the foreign economy? All $X^{(d/f)}M^{(f)}$ rebased traded assets in the domestic economy are martingales under $Q^{XM,d}$. Hence, the domestic values of the foreign traded assets, $X^{(d/f)}Z^{(f)}/X^{(d/f)}M^{(f)} = Z^{(f)}/M^{(f)}$ are also martingales. But this implies (given the uniqueness of a probability measure for a particular numeraire) that $Q^{XM,d}$ and $Q^{M,f}$ are the same probability measure. So under the measure $Q^{M,f}$ all $X^{(d/f)}M^{(f)}$ rebased traded assets are martingales in the domestic economy and all $M^{(f)}$ rebased traded assets are martingales in the foreign economy.

From the domestic economy perspective we have $N^{(d)}$ and $X^{(d/f)}M^{(f)}$ as domestic numeraires. Hence, we can apply the single-currency change of numeraire theorem which yields

$$\frac{\mathrm{d}Q^{N,d}}{\mathrm{d}Q^{M,f}} = \frac{N^{(d)}(T)}{X^{(d/f)}(T)M^{(f)}(T)}\frac{X^{(d/f)}(0)M^{(f)}(0)}{N^{(d)}(0)}. \tag{2}$$

On the other hand, from the foreign perspective we have $X^{(f/d)}N^{(d)}$ and $M^{(f)}$ as foreign numeraires. Hence, we can apply the single-currency change of numeraire theorem to this case as well which yields

$$\frac{\mathrm{d}Q^{N,d}}{\mathrm{d}Q^{M,f}} = \frac{X^{(f/d)}(T)N^{(d)}(T)}{M^{(f)}(T)}\frac{M^{(f)}(0)}{X^{(f/d)}(0)N^{(d)}(0)}. \tag{3}$$

Note that equations (2) and (3) are identical since $X^{(f/d)} = 1/X^{(d/f)}$. Hence, we have derived the following result[4].

Multi-currency change of numeraire. *Given an arbitrage-free system of economies* (d, f)*, an exchange rate* X *and two numeraires* $N^{(d)}$ *and* $M^{(f)}$ *within the economies with the associated martingale measures* $Q^{N,d}$ *and* $Q^{M,f}$ *we have that*

$$\begin{aligned}\frac{\mathrm{d}Q^{N,d}}{\mathrm{d}Q^{M,f}} &= \frac{N^{(d)}(T)}{X^{(d/f)}(T)M^{(f)}(T)}\frac{X^{(d/f)}(0)M^{(f)}(0)}{N^{(d)}(0)}\\ &= \frac{X^{(f/d)}(T)N^{(d)}(T)}{M^{(f)}(T)}\frac{M^{(f)}(0)}{X^{(f/d)}(0)N^{(d)}(0)}.\end{aligned} \tag{4}$$

If we set $X \equiv 1$ the multi-currency change of numeraire theorem reduces to the single-currency case.

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[3] These results have been derived previously by Pedersen and Miltersen (2000) and Schlögl (2002).

[4] This result has previously been derived by Frey and Sommer (1996) and Schlögl (2002).

3. Convexity correction for single currency

Given the change of numeraire theorems, we are now in a position to investigate convexity correction. Convexity correction arises when an interest rate is paid out at the 'wrong' time and/or in the 'wrong' currency.

Suppose we are given a forward interest rate y with maturity T (which can be, for example, a forward LIBOR rate or a forward par swap rate) and a numeraire P such that the forward rate y is a martingale under the associated probability measure Q^P. In the single-currency case we can have a contract where the interest rate $y(T)$ is observed at T but paid at a later date $S \geqslant T$. If we denote the discount bond that matures at S by D_S, we have that the value of this contract at time T is given by $V(T) = y(T)D_S(T)$. Using D_S as the numeraire with the associated forward measure Q^S we can express the value of this contract at time 0 as

$$V(0) = D_S(0)\boldsymbol{E}^S(y(T)). \tag{5}$$

However, under the measure Q^S the process y is in general not a martingale. Expectation (5) can be expressed as $y(0)$ times a correction term. This correction term is known in the market as the *convexity correction* or *convexity adjustment*. Using (5) market participants calculate the value of the pay-off as the discounted value of the convexity-corrected pay-off $\boldsymbol{E}^S(y)$. What remains to be done is to find an expression for $\boldsymbol{E}^S(y)$.

We do know the process of y under its 'own' martingale measure Q^P. Using the change of numeraire theorem, we can express the Q^S-expectation $\boldsymbol{E}^S$ in terms of a Q^P-expectation $\boldsymbol{E}^P$ as follows:

$$\begin{aligned}\boldsymbol{E}^S(y(T)) &= \boldsymbol{E}^P\left(y(T)\frac{\mathrm{d}Q^S}{\mathrm{d}Q^P}\right)\\ &= \boldsymbol{E}^P\left(y(T)\frac{D_S(T)}{P(T)}\frac{P(0)}{D_S(0)}\right) = \boldsymbol{E}^P(y(T)R(T))\end{aligned} \tag{6}$$

where R denotes the Radon–Nikodym derivative (with $R(0) = 1$). Both y and R are martingales under the measure Q^P. If we know the joint probability distribution of $y(T)$ and $R(T)$ the expectation can be calculated explicitly and we obtain an expression for the convexity correction.

One possible approach is to assume that both $y(T)$ and $R(T)$ have lognormal distributions. Hence, for $0 \leqslant t \leqslant T$ we assume that $y(t)$ follows the process $\mathrm{d}y = \sigma_y y\,\mathrm{d}W_y$ and $R(t)$ follows the process $\mathrm{d}R = \sigma_R R\,\mathrm{d}W_R$ under the measure Q^P with correlation $\mathrm{d}W_y\,\mathrm{d}W_R = \rho_{y,R}\,\mathrm{d}t$. Under this assumption we can calculate (6) as

$$\boldsymbol{E}^S(y(T)) = \boldsymbol{E}^P(y(T)R(T)) = y(0)\mathrm{e}^{\rho_{y,R}\sigma_y\sigma_R T}. \tag{7}$$

Note that the Radon–Nikodym derivative $R(t)$ is a ratio of traded assets whose values can be observed in the market. Hence, the instantaneous volatility and the correlation of the $R(t)$ process (which remain unaffected by a change of measure) can be estimated from historical data.

3.1. Example: LIBOR in arrears

Let us consider an example where we can obtain an exact expression for a single-currency convexity correction. In a normal LIBOR payment, the LIBOR interest rate L is observed at time T and paid at the end of the accrual period at time $T+\Delta$ as $\alpha L(T)$, where α denotes the daycount fraction for the time period $[T, T+\Delta]$. The forward LIBOR rate $L(t)$ is defined as

$$L(t) = \frac{1}{\alpha}\frac{D_T(t) - D_{T+\Delta}(t)}{D_{T+\Delta}(t)}, \tag{8}$$

where D_T, $D_{T+\Delta}$ denote discount factors that mature at times T and $T+\Delta$ respectively. Hence, if we choose $D_{T+\Delta}$ as the numeraire then under the associated martingale measure $Q^{T+\Delta}$ the forward LIBOR rate L is a martingale.

In a LIBOR in arrears contract, the interest payment at time T is based on the rate $L(T)$. Hence, the LIBOR payment is fixed only at the end of the interest rate period $[T-\Delta, T]$. The pay-off of a LIBOR in arrears payment at time T is therefore equal to $V^{\mathrm{LIA}}(T) = L(T)$. The value at time 0 of this payment is given by $V^{\mathrm{LIA}}(0) = D_T(0)\boldsymbol{E}^T(L(T)) = D_T(0)\tilde{L}$, where $\tilde{L}$ denotes the convexity-corrected forward LIBOR rate to reflect the payment in arrears. To calculate the convexity correction we proceed as follows. From the change of numeraire theorem we obtain that the Radon–Nikodym derivative for the change of measure $\mathrm{d}Q^{T+\Delta}/\mathrm{d}Q^T$ is given by the ratio of the numeraires

$$\frac{\mathrm{d}Q^T}{\mathrm{d}Q^{T+\Delta}} = \frac{D_T(T)}{D_{T+\Delta}(T)}\frac{D_{T+\Delta}(0)}{D_T(0)}. \tag{9}$$

Using the definition (8) we can rewrite the Radon–Nikodym derivative as[5]

$$\frac{\mathrm{d}Q^T}{\mathrm{d}Q^{T+\Delta}} = \frac{1+\alpha L(T)}{1+\alpha L(0)}. \tag{10}$$

Using this expression we can calculate $\tilde{L}$ as

$$\begin{aligned}\tilde{L} &= \boldsymbol{E}^T(L(T)) = \boldsymbol{E}^{T+\Delta}\left(L(T)\frac{\mathrm{d}Q^T}{\mathrm{d}Q^{T+\Delta}}\right)\\ &= \frac{\boldsymbol{E}^{T+\Delta}(L(T)(1+\alpha L(T)))}{1+\alpha L(0)}\\ &= \frac{L(0)+\alpha \boldsymbol{E}^{T+\Delta}(L(T)^2)}{1+\alpha L(0)}.\end{aligned} \tag{11}$$

The expression above is valid irrespective of the distribution of L. If we make the additional assumption that the forward LIBOR rate has a lognormal distribution under the measure $Q^{T+\Delta}$ we have that $\boldsymbol{E}^{T+\Delta}(L(T)^2) = L(0)^2\mathrm{e}^{\sigma^2 T}$ and we obtain

$$\tilde{L} = L(0)\left(\frac{1+\alpha L(0)\mathrm{e}^{\sigma^2 T}}{1+\alpha L(0)}\right) \tag{12}$$

where σ denotes the volatility[6] of L.

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[5] The relationship between forward measures to the beginning and end of a forward LIBOR accrual period was first presented by Musiela and Rutkowski (1997).

[6] Note that the LIBOR in arrears convexity correction approximation given in Hull (2000, p 553) is to first order equal to the exact formula (12). The exact expressions for LIBOR in arrears have also been derived by Jamshidian (1997), Rutkowski (1998) and Pugachevsky (2001).

4. Convexity correction for multi-currency

Let us now consider the multi-currency case. In this case we have a contract where a foreign interest rate $y^{(f)}(T)$ is observed at T but paid in domestic currency at a later date $S \geqslant T$. If we denote the domestic discount bond that matures at S by $D_S^{(d)}$, we have that the value of this contract in domestic terms at time T is given by $V^{(d)}(T) = y^{(f)}(T)D_S^{(d)}(T)$. Using $D_S^{(d)}$ as the numeraire and the associated measure $Q^{S,d}$ we can express the value of this contract at time 0 as

$$V^{(d)}(0) = D_S^{(d)}(0)E^{S,d}(y^{(f)}(T)). \tag{13}$$

However, under the measure $Q^{S,d}$ the process $y^{(f)}$ is in general not a martingale. We do know the process of $y^{(f)}$ under its 'own' martingale measure $Q^{P,f}$. Using the change of numeraire theorem, we can express the expectation $E^{S,d}$ in terms of $E^{P,f}$ as follows:

$$\begin{aligned} E^{S,d}(y^{(f)}(T)) &= E^{P,f}\left(y^{(f)}(T)\frac{\mathrm{d}Q^{S,d}}{\mathrm{d}Q^{P,f}}\right) \\ &= E^{P,f}(y^{(f)}(T)R^{(d/f)}(T)). \end{aligned} \tag{14}$$

Just like the single-currency case the Radon–Nikodym derivative $R^{(d/f)}$ is a ratio of traded assets whose values can be observed in the market. Hence, the volatility and the correlation of the $R^{(d/f)}$ process (which remain unaffected by a change of measure) can be estimated from historical data. Another approach to evaluate (14) is to decompose $R^{(d/f)}$ as the forward exchange rate times $D_S^{(f)}/P^{(f)}$, which is the single-currency Radon–Nikodym derivative of equation (6). This leads to the expression

$$\begin{aligned} E^{S,d}(y^{(f)}(T)) &= E^{P,f}\left(y^{(f)}(T)\frac{\mathrm{d}Q^{S,d}}{\mathrm{d}Q^{P,f}}\right) \\ &= E^{P,f}\left(y^{(f)}(T)\left(X^{(f/d)}(T)\frac{D_S^{(d)}(T)}{P^{(f)}(T)}\right)\right)\frac{P^{(f)}(0)}{X^{(f/d)}(0)D_S^{(d)}(0)} \\ &= E^{P,f}\left(y^{(f)}(T)\left(X^{(f/d)}(T)\frac{D_S^{(d)}(T)}{D_S^{(f)}(T)}\right)\frac{D_S^{(f)}(T)}{P^{(f)}(T)}\right) \\ &\quad\times\frac{P^{(f)}(0)}{X^{(f/d)}(0)D_S^{(d)}(0)} \\ &= E^{P,f}\left(y^{(f)}(T)F_S^{(f/d)}(T)\frac{D_S^{(f)}(T)}{P^{(f)}(T)}\right) \\ &\quad\times\frac{P^{(f)}(0)}{X^{(f/d)}(0)D_S^{(d)}(0)}, \end{aligned} \tag{15}$$

where F_S denotes the forward exchange rate for delivery at time S. The volatility of the forward exchange rate is quoted in the market as the implied volatility of a foreign exchange option with maturity S. The process F_S is not a martingale under the measure $Q^{P,f}$, but the drift of the process can be determined from the fact that $D_S^{(f)}/P^{(f)}$ and $F_S D_S^{(f)}/P^{(f)}$ are martingales under $Q^{P,f}$. Hence, expression (15) can be used for explicit computations for cross currency convexity corrections.

4.1. Example: diffed LIBOR

For a *diffed* LIBOR contract (also known as quantoed LIBOR) a foreign LIBOR rate $L^{(f)}$ is observed at T and is paid in domestic currency at time $T + \Delta$. These diffed LIBOR payments are often paid in the form of a *differential swap* or diff swap. In a diff swap a floating interest rate in the foreign currency is exchanged against a floating rate in the domestic currency where both rates are applied to the same domestic notional principal. The domestic leg of a diff swap can be valued as a standard floating leg in the domestic currency. The foreign leg of the diff swap is a portfolio of diffed foreign LIBOR payments, and its value can be calculated as the sum of the individual diffed LIBOR payments.

For diffed LIBOR the expression (15) reduces to

$$E^{T+\Delta,d}(L^{(f)}(T)) = E^{T+\Delta,f}(L^{(f)}(T)F_{T+\Delta}^{(f/d)}(T))\frac{1}{F_{T+\Delta}^{(f/d)}(0)}. \tag{16}$$

If we make the approximating assumption that the forward LIBOR rate and the forward exchange rate have lognormal distributions under $Q^{T+\Delta,f}$, then the convexity-corrected foreign LIBOR rate $\tilde{L}_i^{(f)}$ is given by[7]

$$\tilde{L}_i^{(f)} = L_i^{(f)}(0)\mathrm{e}^{\rho_{F,L}\sigma_F\sigma_L T}, \tag{17}$$

where the volatility of the forward exchange rate with delivery at time $T+\Delta$ is denoted by σ_F. Here σ_L denotes the volatility of the foreign LIBOR rate $L^{(f)}$ and $\rho_{F,L}$ denotes the correlation between the forward (f/d) exchange rate and $L^{(f)}$. By the exchange rate (f/d) we mean the value of one unit of domestic currency in terms of foreign currency.

Note that the approximating assumption that both the LIBOR rates and the forward exchange rates have lognormal distributions is unlikely to be satisfied in practice. The assumption is, for example, incompatible with the case of lognormal models for the forward LIBOR rates combined with the usual assumption that the volatility of the spot exchange rate is deterministic. This case is examined in Musiela and Rutkowski (1997, section 17.3).

For many practical applications, the correlation between the forward exchange rate and the forward LIBOR rate is approximated by the correlation between the spot exchange rate and the spot LIBOR rate[8].

Note that, using formula (15), one can also derive an exact expression for diffed LIBOR in arrears, but the formula is rather tedious and therefore omitted from this paper.

5. Simple approximation formula for convexity correction

Only for very special cases can exact expressions for the convexity correction be obtained. In these special cases the Radon–Nikodym derivative of the change of measure is equal to a simple function of the interest rate that determines the pay-off. A point in case is LIBOR in arrears. In this section we want to propose a method to approximate convexity corrections that exploits the idea of making the Radon–Nikodym derivative a function of the payout rate.

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[7] Formulae for diffed LIBOR have been derived previously by Pedersen and Miltersen (2000) and Schlögl (2002).

[8] Note that, if we calculate the correlation between the forward (d/f) exchange rate and $L^{(f)}$, we must use $-\rho$ in our formula.

5.1. Approximation for single currency

For derivative contracts with a pay-off based on an interest rate y, the numeraire that makes the interest rate a martingale is always a portfolio of discount bonds of the form $\sum_i \alpha_{i-1} D_i$. Let us denote this numeraire by P. In the general (single-currency) case we have that the interest rate is observed at time T, and paid out at time $S \geqslant T$. Hence, the Radon–Nikodym derivative is of the form $R(T) = D_S(T)/P(T)$.

The LSM[9] of Hunt and Kennedy (2000) provides us with a convenient way to approximate $R(T)$. In this model one approximates $D_S(T)/P(T)$ by the linear form $A + B_S y(T)$, where $A = (\sum_i \alpha_{i-1})^{-1}$ and $B_S = (D_S(0)/P(0) - A)/y(0)$. Note that A is a constant and B_S only depends on the maturity S. Using this approximation we can evaluate (6) explicitly as

$$\begin{aligned}
\boldsymbol{E}^S(y(T)) &= \frac{P(0)}{D_S(0)}\boldsymbol{E}^P\left(y(T)\frac{D_S(T)}{P(T)}\right) \\
&= \frac{P(0)}{D_S(0)}\boldsymbol{E}^P(y(T)(A + B_S y(T))) \\
&= y(0)\left(\frac{A + B_S y(0)\mathrm{e}^{\sigma_y^2 T}}{A + B_S y(0)}\right). \qquad (18)
\end{aligned}$$

The linear approximation of the LSM does seem very crude at first, but can be justified by the following argument. Convexity corrections only become sizeable for large maturities. However, for large maturities the term structure almost moves in parallel. Hence, a change in the level of the long end of the curve is well described by the swap rate. Furthermore, for parallel moves in the curve, the *ratio* $D_S(T)/P(T)$ is closely approximated by a linear function of the swap rate, which is exactly what the LSM does. Hence, exactly for long maturities the assumptions of the LSM become quite accurate. This leads to a good approximation of the convexity correction for long maturities.

5.2. Example: constant maturity swap

A particularly liquid type of exotic European interest rate contract is a *constant maturity swap* (or CMS). This is a swap where at every payment date a payment calculated from a swap rate y is exchanged for a fixed rate. Usually, these payments are treated as floating payments: at the preceding payment date T the swap rate $y(T)$ is observed, the actual payment is made at the next payment date S. Hence, each CMS payment consists of a swap rate y that is observed at time T and paid out (only once) at time $S \geqslant T$. Note that the term and payment frequency of the swap rate may be different from the specifications of the CMS swap itself.

The forward swap rate $y(t)$ is defined as $(D_0(t) - D_N(t))/P(t)$, where D_0 has a maturity equal to the start date T of the swap, D_N has a maturity equal to the last payment date T_N of the swap and $P(t)$ is the present value of a basis point (or PVBP) of the swap given by $\sum_i \alpha_{i-1} D_i(t)$ where the D_i are the discount factors with maturity dates equal to the dates at which fixed payments are made in the swap. If we use the PVBP $P(t)$ as a numeraire, then the forward swap rate $y(t)$ is a martingale under the measure[10] Q^P. To calculate the value of a CMS payment at time 0 we use the convexity-corrected swap rate $\tilde{y}$ given by (18).

Table 1. Forward 20 year CMS rate $y(T)$ paid at $T + 1$. Simulations based on 500 000 runs in a two-factor LIBOR market model with volatility specification $\Lambda^1(T) = 0.256\exp\{-0.145T\}$, $\Lambda^2(T) = 7.334\exp\{-4.096T\}$ and correlation -0.744 between the factors. The initial term structure of LIBOR rates is flat at 5%.

T	σ_{LIBOR} (%)	σ_{Swap} (%)	LMM (%)	StdErr (%)	LSM (%)
1	15.5	11.8	5.017	0.001	5.024
2	17.5	11.3	5.032	0.002	5.045
3	17.2	10.8	5.044	0.002	5.061
4	16.6	10.2	5.053	0.002	5.073
5	15.8	9.7	5.064	0.002	5.083
6	15.1	9.2	5.067	0.002	5.090
7	14.4	8.7	5.070	0.002	5.095
8	13.8	8.3	5.073	0.002	5.099
9	13.2	8.0	5.073	0.002	5.102
10	12.7	7.6	5.074	0.002	5.103
11	12.2	7.3	5.075	0.002	5.105
12	11.8	7.0	5.075	0.003	5.106
13	11.4	6.8	5.073	0.003	5.106
14	11.0	6.5	5.072	0.003	5.107
15	10.6	6.3	5.073	0.003	5.107
16	10.3	6.1	5.075	0.003	5.107
17	10.0	5.9	5.078	0.003	5.107
18	9.8	5.8	5.078	0.003	5.106
19	9.5	5.6	5.075	0.003	5.105
20	9.3	5.4	5.074	0.003	5.104

Let us compare the convexity correction formula (18) with Monte Carlo simulations in a two-factor LIBOR market model (LMM)[11]. In table 1 we have summarized the results for the expectation $\boldsymbol{E}^{T+1}(y_{20}(T))$ simulated in a two-factor LMM with annual LIBOR rates. The volatility functions of the LIBOR rates are given by $\Lambda^1(T) = 0.256\exp\{-0.145T\}$ and $\Lambda^2(T) = 7.334\exp\{-4.096T\}$. The correlation between the two factors is given by -0.744. Hence, we have a model with two negatively correlated factors, where the first factor has a low mean reversion of 0.145 and the second factor has a high mean reversion of 7.334. As shown in the second and third columns of table 1, we replicate with this volatility specification for the LMM the volatility hump of LIBOR rates and a declining volatility structure for 20 year swap rates which is consistent with empirical observations.

Using a market model with annual time-steps we have simulated the value of 20 year swap rates observed at time T which are paid at time $T+1$ for $T = 1, \ldots, 20$. For this pay-off scheme typically observed in CMS swaps, one cannot apply standard Taylor series based convexity correction formulae (as proposed in Hull 2000, chapter 20) without introducing additional correlations between the forward swap rate and the forward 1 year rate.

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[9] See the appendix for a brief derivation of this model.

[10] This was first pointed out by Jamshidian (1997).

[11] For further details on the implementation of a Monte Carlo simulation in a multi-factor LMM, we refer to Hull (2000, chapter 22), or Pelsser (2000, chapter 8).

From table 1 we see that the approximations calculated with the LSM formula (18) (see column 'LSM') are very close to the Monte Carlo simulation in the two-factor LMM (see column 'LMM'). We do see that the LSM formula over-estimates the convexity correction somewhat. This effect can be attributed to the fact that the LSM is a one-factor model which tends to over-estimate the correlation between different interest rates.

5.3. Approximation for multi-currency

Let us consider the use of the LSM in the multi-currency case. In the foreign economy, we approximate $D_S^{(f)}/P^{(f)}$ by $A^{(f)} + B_S^{(f)} y^{(f)}$. First, we determine the expected value of the forward exchange rate F from the fact that the Radon–Nikodym derivative $R^{(d/f)} = F_S^{(f/d)}(T) D_S^{(f)}(T)/P^{(f)}(T)$ is a martingale under the measure $\boldsymbol{Q}^{P,f}$. We have

$$
\begin{aligned}
F_S^{(f/d)}(0)\frac{D_S^{(f)}(0)}{P^{(f)}(0)} &= \boldsymbol{E}^{P,f}\left(F_S^{(f/d)}(T)\frac{D_S^{(f)}(T)}{P^{(f)}(T)}\right)\\
&= \boldsymbol{E}^{P,f}(F_S^{(f/d)}(T)(A^{(f)} + B_S^{(f)} y^{(f)}(T)))\\
&= A^{(f)}\boldsymbol{E}^{P,f}(F_S^{(f/d)}(T))\\
&\quad + B_S^{(f)}\boldsymbol{E}^{P,f}(F_S^{(f/d)}(T)) y^{(f)}(0) \mathrm{e}^{\rho_{F,y}\sigma_F\sigma_y T}, \qquad (19)
\end{aligned}
$$

where we have made the (market standard) assumption that F is a lognormal process; furthermore, the volatility of F is denoted by σ_F and $\rho_{F,y}$ denotes the correlation between F and y. We can now solve for $\boldsymbol{E}^{P,f}(F_S^{(f/d)}(T))$ to obtain

$$
\begin{aligned}
&\boldsymbol{E}^{P,f}(F_S^{(f/d)}(T))\\
&\quad = F_S^{(f/d)}(0)\left(\frac{A^{(f)} + B_S^{(f)} y^{(f)}(0)}{A^{(f)} + B_S^{(f)} y^{(f)}(0)\mathrm{e}^{\rho_{F,y}\sigma_F\sigma_y T}}\right). \qquad (20)
\end{aligned}
$$

Given this expression, we can evaluate the cross-currency expectation (15) as

$$
\begin{aligned}
&\boldsymbol{E}^{S,d}(y^{(f)}(T)) = y^{(f)}(0)\\
&\quad \times\left(\mathrm{e}^{\rho_{F,y}\sigma_F\sigma_y T}\frac{A^{(f)} + B_S^{(f)} y^{(f)}(0)\mathrm{e}^{(\sigma_y^2+\rho_{F,y}\sigma_F\sigma_y)T}}{A^{(f)} + B_S^{(f)} y^{(f)}(0)\mathrm{e}^{\rho_{F,y}\sigma_F\sigma_y T}}\right). \qquad (21)
\end{aligned}
$$

Note that this expression depends on the F and the $y^{(f)}$ volatility which can both be observed in the market; the correlation $\rho_{F,y}$ between the forward F/X process and the forward swap rate process also enters the formula.

Note also that, if we set $\rho_{F,y} = 0$ or $\sigma_F = 0$, then the cross-currency formula (21) reduces to the single-currency formula (18).

6. Options on convexity-corrected rates

Not only are we interested in interest rates paid in different currencies and/or at different times, but also we want to value call and put options and digital options on these rates. Using the change of numeraire theorem, we can proceed exactly as before.

Take for example a call option on a foreign interest rate observed at time T and paid in domestic currency at a later date $S \geqslant T$. The value of such a contract at time T is given by $V^{(d)}(T) = D_S^{(d)}(T)\max\{y^{(f)}(T) - K, 0\}$. We can value this pay-off as

$$
\begin{aligned}
V^{(d)}(0) &= D_S^{(d)}(0)\boldsymbol{E}^{S,d}(\max\{y^{(f)}(T) - K, 0\}) \qquad (22)\\
&= D_S^{(d)}(0)\boldsymbol{E}^{P,f}(\max\{y^{(f)}(T) - K, 0\}R^{(d/f)}(T)) \qquad (23)\\
&= D_S^{(d)}(0)\boldsymbol{E}^{P,f}(\max\{y^{(f)}(T)R^{(d/f)}(T) - KR^{(d/f)}(T), 0\}). \qquad (24)
\end{aligned}
$$

The last line can be interpreted as an exchange option between yR and KR. We know that y is a lognormal martingale under the measure $\boldsymbol{Q}^{P,f}$. In general the processes $y(t)R(t)$ and $KR(t)$ are not lognormal processes under the measure $\boldsymbol{Q}^{P,f}$. If we approximate the probability distributions of $y(T)R(T)$ and $KR(T)$ by lognormal distributions, the option value can then be evaluated by the Margrabe (1978) formula as follows:

$$
\begin{aligned}
V^{(d)}(0) &= D_S^{(d)}(0)(E_1 N(d_1) - E_2 N(d_2)),\\
E_1 &= \boldsymbol{E}^{P,f}(y^{(f)}(T)R^{(d/f)}(T)),\\
E_2 &= \boldsymbol{E}^{P,f}(KR^{(d/f)}(T)) = K,\\
d_{1,2} &= \frac{\log(E_1/E_2) \pm \frac{1}{2}\Sigma^2}{\Sigma}, \qquad (25)\\
\Sigma^2 &= \mathrm{var}^{P,f}\left(\log\left(\frac{y^{(f)}(T)R^{(d/f)}(T)}{KR^{(d/f)}(T)}\right)\right)\\
&= \mathrm{var}^{P,f}(\log y^{(f)}(T)) = \sigma_y^2 T.
\end{aligned}
$$

The expression for E_1 is the convexity-corrected forward rate which can be denoted by $\tilde{y}^{(f)}$. Hence, we can simplify the expression above to obtain

$$
\begin{aligned}
V^{(d)}(0) &= D_S^{(d)}(0)(\tilde{y}^{(f)}N(d_1) - KN(d_2)),\\
d_{1,2} &= \frac{\log(\tilde{y}^{(f)}/K) \pm \frac{1}{2}\sigma_y^2 T}{\sigma_y\sqrt{T}}, \qquad (26)
\end{aligned}
$$

which is the market standard method of valuing options on convexity-corrected rates and says 'apply the Black formula using the convexity-corrected rate as the forward rate'.

For the cases where we approximate the Radon–Nikodym derivative with the LSM, the approximation results in an expression for the Radon–Nikodym derivative which is not exactly lognormally distributed. However, the market standard method will be a good approximation.

Acknowledgments

The author would like to thank participants of the *Maths Week 2000* conference in London and the *Dutch Mathematical Conference* in Amsterdam, Jeroen Kerkhof, Marek Rutkowski and two anonymous referees for their comments and suggestions.

Appendix

In this appendix we derive the LSM. The LSM is due to Hunt and Kennedy (2000, chapter 13). Let $y(t)$ be a forward par swap rate with swap start date T_0, payment dates $T_1, \ldots, T_N$, $P(t) = \sum_1^N \alpha_{i-1} D_i(t)$ the PVBP of the swap and Q^P the martingale measure associated with the numeraire P. The swap rate $y(t)$ is defined as $y(t) = (D_0(t) - D_N(t))/P(t)$ and is therefore a martingale under Q^P. Define $\hat{D}_S(t) = D_S(t)/P(t)$, then $\hat{D}_S(t)$ is also a martingale under the measure Q^P.

In the LSM the assumption is made that $\hat{D}_S(T_0) = A + B_S y(T_0)$, where A is a constant and B_S is a deterministic function of S. Hence, it is assumed that the PVBP rebased discount factor $\hat{D}_S$ can be approximated by a linear expression in the swap rate y. Let us solve for the parameter A and the function B_S for $S \geqslant T_0$. We know that $\hat{D}_S$ should be a martingale. To check the martingale property we consider

$$\begin{aligned}\hat{D}_S(0) &= \frac{D_S(0)}{P(0)} = E^P(\hat{D}_S(T_0)) \\ &= E^P(A + B_S y(T_0)) = A + B_S y(0).\end{aligned}$$

The martingale property of $\hat{D}_S$ is ensured if we set

$$B_S = \frac{D_S(0)/P(0) - A}{y(0)}.$$

The parameter A can be determined as follows. Consider the identity $\sum_1^N \alpha_{i-1} \hat{D}_i(t) \equiv 1$. Expanding this expression yields

$$1 \equiv \underset{\underset{1}{\Downarrow}}{\left(A \sum_{i=1}^{N} \alpha_{i-1}\right)} + \underset{\underset{0}{\Downarrow}}{\left(\sum_{i=1}^{N} \alpha_{i-1} B_{T_i}\right)} y(t).$$

Hence, we find $A = 1/\sum_1^N \alpha_{i-1}$. It is left as an exercise for the reader to check the condition on the B_{T_i}.

Note that, if y is a forward LIBOR rate L_i, then we have that $P(t) = \alpha D_{T+\Delta}(t)$. The LSM model now generates the following expression:

$$\hat{D}_T(t) = \frac{D_T(t)}{\alpha_i D_{T+\Delta}(t)} = A + B_T L = \frac{1}{\alpha} + L(t),$$

which reflects exactly the definition of the forward LIBOR rate L_i.

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