

Self-dual continuous processes

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Abstract

The important application of semi-static hedging in financial markets naturally leads to the notion of conditionally quasi self-dual processes which is, for continuous semimartingales, related to conditional symmetry properties of both their ordinary as well as their stochastic logarithms. We provide a structure result for continuous conditionally quasi self-dual processes. Our main result is to give a characterization of continuous Ocone martingales via a strong version of self-duality.

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1. Introduction

The duality principle in option pricing relates different financial products by a certain change of measure. It allows to transform complicated financial derivatives into simpler ones in a suitable dual market. For a comprehensive treatment, see [6,7] and the literature cited therein.

Sometimes it is even possible to semi-statically hedge path-dependent barrier options with European ones. These are options which only depend on the asset price at maturity. Here semi-static refers to trading at most at inception and a finite number of stopping times like hitting times of barriers. The possibility of this hedge, however, requires a certain symmetry property of the asset price which has to remain invariant under the duality transformation, possibly after a power

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transform. This leads naturally to the concepts of self-duality, resp. quasi self-duality; see [2] and more recently [3,15]. For references to the large literature of the special case of put-call symmetry, see [3,8–10,22].

Continuous symmetric processes have been characterized in [22], and it is shown therein that the conditional symmetry property is related to the conditional self-duality of their stochastic exponentials. We extend this study by exploring the structure of conditionally quasi self-dual processes as well as characterizing continuous Ocone martingales using results from [23] and a strong version of self-duality. Ocone martingales are a very important class of conditionally symmetric martingales; indeed, Tehranchi raised in [22] the question whether *all* conditionally symmetric martingales are Ocone. This question is still open. We do provide, however, an example of a non-Ocone martingale in continuous time which is process, but not conditionally symmetric.

2. Definitions and general properties

We work on a filtered probability space $(\Omega, \mathcal{F}, \mathbb{F}, P)$ where unless otherwise stated, the filtration satisfies the usual conditions with \mathcal{F}_0 being trivial up to P -null sets, and fix a finite but arbitrary time horizon $T > 0$. All stochastic processes are RCLL and defined on $[0, T]$ unless otherwise stated. We understand positive and negative in the strict sense.

Definition 1. Let M be an adapted process. M is *conditionally symmetric* if for any stopping time $\tau \in [0, T]$ and any non-negative Borel function f

$$E[f(M_T - M_\tau) | \mathcal{F}_\tau] = E[f(M_\tau - M_T) | \mathcal{F}_\tau]. \quad (1)$$

Here it is permissible that both sides of the equation are infinite. If M is an integrable conditionally symmetric process, then condition (1) implies that M is a martingale by choosing $f(x) = x (=x^+ - x^-)$.

Definition 2. Let S be a positive adapted process. S is *conditionally self-dual* if for any stopping time $\tau \in [0, T]$ and any non-negative Borel function f we have

$$E\left[f\left(\frac{S_T}{S_\tau}\right) \middle| \mathcal{F}_\tau\right] = E\left[\frac{S_T}{S_\tau} f\left(\frac{S_\tau}{S_T}\right) \middle| \mathcal{F}_\tau\right]. \quad (2)$$

These definitions are new, and are motivated by the fact that in applications to semi-static hedging one typically considers hitting times of barriers which are stopping times. They differ from the ones used in [22] which uses bounded measurable f instead, and in particular deterministic times. However, all corresponding results in [22] applied in this paper can be adapted to our setting.

In the case when S is a martingale, we can define a probability measure Q , the so-called *dual measure*, via

$$\frac{dQ}{dP} = \frac{S_T}{S_0}. \quad (3)$$

Similarly, if $E[\sqrt{S_T}] < \infty$, or $E[S_T^w] < \infty$ for a $w \in [0, 1]$, respectively, we define probability measures H , sometimes called ‘half measure’, respectively P^w , via

$$\frac{dH}{dP} = \frac{\sqrt{S_T}}{E[\sqrt{S_T}]}, \quad \frac{dP^w}{dP} = \frac{S_T^w}{E[S_T^w]}. \quad (4)$$

Note that the integrability of $S_T = S_0 \exp(X_T)$ under P implies the existence of the moment generating function of X_T under H for an open interval including the origin, i.e. X_T has all moments under H .

By Bayes' formula, the conditional self-duality condition (2) can be expressed for a martingale S in terms of the dual measure Q defined in (3) as

$$E_P \left[f \left(\frac{S_T}{S_\tau} \right) \middle| \mathcal{F}_\tau \right] = E_Q \left[f \left(\frac{S_\tau}{S_T} \right) \middle| \mathcal{F}_\tau \right]. \quad (5)$$

Lemma 3 ([22, Lemma 3.2]). *A positive continuous martingale S is conditionally self-dual if and only if*

$$E_P \left[\left(\frac{S_T}{S_\tau} \right)^p \middle| \mathcal{F}_\tau \right] = E_P \left[\left(\frac{S_\tau}{S_T} \right)^{1-p} \middle| \mathcal{F}_\tau \right] \quad (6)$$

for all complex $p = a + ib$ with $a \in [0, 1]$ and all stopping times $\tau \in [0, T]$.

For the measure H (corresponding to $w = 1/2$) the following proposition has been stated in slightly different settings in [3,15,22], and also for $w = 1$, i.e. for Q . Similar unconditional multivariate results are given in [16].

Proposition 4. *Let $S = \exp(X)$ be a martingale. Then S is conditionally self-dual if and only if for any stopping time $\tau \in [0, T]$ and any non-negative Borel function f*

$$E_{P^w} [f(X_T - X_\tau) | \mathcal{F}_\tau] = E_{P^{1-w}} [f(X_\tau - X_T) | \mathcal{F}_\tau] \quad (7)$$

holds for at least one (and then necessarily for all) $w \in [0, 1]$.

For the half measure we immediately obtain the following special case.

Corollary 5. *Let $S = \exp(X)$ be a martingale. Then S is conditionally self-dual if and only if X is conditionally symmetric with respect to H .*

Proof of Proposition 4. As a consequence of the martingale property of S and Hölder's inequality we have that both $E_P [e^{w(X_T - X_\tau)} | \mathcal{F}_\tau]$, for all $w \in [0, 1]$, as well as $|E_P [e^{p(X_T - X_\tau)} | \mathcal{F}_\tau]|$, for all complex $p = a + ib$ with $a \in [0, 1]$, $\tau \in [0, T]$, are finite a.s.

Let S be conditionally self-dual, $w \in [0, 1]$, so that (6) implies the following two equalities:

$$E_P [e^{w(X_T - X_\tau)} | \mathcal{F}_\tau] = E_P [e^{(1-w)(X_T - X_\tau)} | \mathcal{F}_\tau], \quad (8)$$

$$E_P [e^{(w+i\theta)(X_T - X_\tau)} | \mathcal{F}_\tau] = E_P [e^{(1-w-i\theta)(X_T - X_\tau)} | \mathcal{F}_\tau], \quad (9)$$

for $\theta \in \mathbb{R}$. By applying Bayes' formula we obtain

$$E_{P^w} [e^{i\theta(X_T - X_\tau)} | \mathcal{F}_\tau] = \frac{E_P [e^{(w+i\theta)(X_T - X_\tau)} | \mathcal{F}_\tau]}{E_P [e^{w(X_T - X_\tau)} | \mathcal{F}_\tau]},$$

$$E_{P^{1-w}} [e^{i\theta(X_\tau - X_T)} | \mathcal{F}_\tau] = \frac{E_P [e^{(1-w-i\theta)(X_T - X_\tau)} | \mathcal{F}_\tau]}{E_P [e^{(1-w)(X_T - X_\tau)} | \mathcal{F}_\tau]},$$

so that in view of (8), (9) the r.h.s. coincide and so do the l.h.s. Since the conditional characteristic functions $(X_T - X_\tau)$ under P^w coincide with the ones of $(X_\tau - X_T)$ under P^{1-w} , we end up with (7) for the claimed cases.

On the other hand, for an arbitrary $w \in [0, 1]$, the P -martingale property of S , and by Bayes' formula we see that the l.h.s. (and hence the r.h.s.) of the following equations coincide:

$$E_P \left[e^{-w(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right] = E_P \left[e^{w(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right]^{-1}, \quad (10)$$

$$\begin{aligned} E_{P^{1-w}} \left[e^{-w(X_\tau - X_T)} \middle| \mathcal{F}_\tau \right] &= \frac{E_P \left[e^{X_T - X_\tau} \middle| \mathcal{F}_\tau \right]}{E_P \left[e^{(1-w)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right]} \\ &= E_P \left[e^{(1-w)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right]^{-1}. \end{aligned} \quad (11)$$

Furthermore, we have for all complex $p = a + ib$ with $a \in [0, 1]$ that

$$E_P \left[e^{(p-w)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right] = E_{P^{1-w}} \left[e^{(w-p)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right].$$

Combining this equality with the fact that the r.h.s. of (10) and (11) coincide we obtain the equality of the l.h.s. of the following two equations

$$\begin{aligned} E_P \left[\frac{e^{p(X_T - X_\tau)}}{e^{w(X_T - X_\tau)}} \middle| \mathcal{F}_\tau \right] E_P \left[e^{w(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right] &= E_P \left[e^{p(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right] \\ E_{P^{1-w}} \left[\frac{e^{(1-p)(X_T - X_\tau)}}{e^{(1-w)(X_T - X_\tau)}} \middle| \mathcal{F}_\tau \right] E_P \left[e^{(1-w)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right] &= E_P \left[e^{(1-p)(X_T - X_\tau)} \middle| \mathcal{F}_\tau \right]. \end{aligned}$$

The conditional self-duality property then follows by using the equality of the r.h.s. of the above equations and Lemma 3. \square

The following definition and proposition follow the unconditional versions stated in [15]; see also [3].

Definition 6. An adapted positive process S is *conditionally quasi self-dual* of order $\alpha \in \mathbb{R}$ if for any stopping time $\tau \leq T$ and any non-negative Borel function f it holds that

$$E_P \left[f \left(\frac{S_T}{S_\tau} \right) \middle| \mathcal{F}_\tau \right] = E_P \left[\left(\frac{S_T}{S_\tau} \right)^\alpha f \left(\frac{S_\tau}{S_T} \right) \middle| \mathcal{F}_\tau \right]. \quad (12)$$

In particular, for all $\tau \leq T$

$$E_P \left[\left(\frac{S_T}{S_\tau} \right)^\alpha \middle| \mathcal{F}_\tau \right] = 1.$$

Proposition 7 (Characterization of Conditional Quasi Self-Duality). S is conditionally quasi self-dual of order $\alpha \neq 0$ if and only if S^α is conditionally self-dual.

Proof. This follows by considering for each f the functions g defined by $g(x) = f(x^\alpha)$, respectively h given by $h(x) = f(x^{1/\alpha})$, $x > 0$. \square

3. Conditionally quasi self-dual continuous martingales

The goal of this section is to clarify the structure of conditionally quasi self-dual processes in a continuous martingale setting which comprises some Brownian motion-driven stochastic volatility models in financial applications. Following [22] we assume throughout this section that every (\mathcal{F}_t) -martingale is continuous. We refer the reader to [19] for all unexplained terminologies.

For every continuous conditionally symmetric martingale Y , $Y_0 = 0$, such that its stochastic exponential $\mathcal{E}(Y)$ is a martingale, one can define the change of measure

$$\frac{dQ}{dP} = \mathcal{E}(Y)_T = \exp\left(Y_T - \frac{1}{2}[Y]_T\right).$$

In the sequel, we assume that Y is a continuous martingale with $Y_0 = 0$. Let $X = Y - \frac{1}{2}[Y]$ and observe that $[X] = [Y]$, hence $Y = X + \frac{1}{2}[X]$. We assume w.l.o.g. that $S_0 = 1$ and set $S = \exp(X) = \mathcal{E}(Y)$. By Corollary 5, the conditional self-duality of a martingale S is equivalent to the conditional symmetry of X under the measure H . The next result is significantly more difficult to prove.

Theorem 8 (Tehranchi [22, Theorem 3.1]). *The continuous martingale S is conditionally self-dual if and only if S is of the form $S = \mathcal{E}(Y)$ for a conditionally symmetric continuous local martingale Y .*

One particular problem in this context is that stochastic exponentials can be strict local martingales in which case it would not be possible to use them as density processes for the measure transform leading to the dual market in financial interpretations. An example class of positive conditionally self-dual continuous martingales is provided by stochastic exponentials of conditionally symmetric *BMO*-martingales; see [13] for a detailed exposition of *BMO*-theory.

Proposition 9. *Let Y be a continuous conditionally symmetric martingale such that there exists a constant C with*

$$\sup_{0 \leq \tau \leq T} E[|Y_T - Y_\tau| | \mathcal{F}_\tau] \leq C. \quad (13)$$

*Then Y is a *BMO*-martingale and its stochastic Doléans-exponential $\mathcal{E}(\alpha Y)$ is a martingale for each $\alpha \in \mathbb{R}$. Moreover, the following two assertions are equivalent.*

- (i) *$S = \mathcal{E}(Y)$ is a positive conditionally self-dual martingale which satisfies for some $p > 1$ the reverse Hölder inequality $R_p(P)$, or, equivalently the Muckenhoupt inequality $A_q(Q)$ for $q = (p + 1)/p$, both with the same constant.*
- (ii) *Y is a conditionally symmetric *BMO*-martingale.*

Proof. Condition (13) implies that $Y \in \text{BMO}$. Consequently, by Theorem 2.3 in [13], $\mathcal{E}(\alpha Y)$ is a martingale (and not a strict local martingale).

The uniform boundedness for all stopping times of the l.h.s. of (5) for $f(x) = |x|^p$ corresponds to $R_p(P)$, and of the r.h.s. of (5) for $f(x) = |x|^q$ to $A_q(Q)$. The equivalence of (i) and (ii) then follows from Theorems 2.3, 2.4 and 3.4 in [13], together with Theorem 8. \square

The process $X = \log(S)$ is, in contrast to Y , typically not a martingale. As $X = Y - \frac{1}{2}[Y]$, the minimal martingale measure \widehat{P} (see [21]) for X is well-defined if $\mathcal{E}\left(\frac{1}{2}Y\right)$ is a martingale, and has then the density

$$\frac{d\widehat{P}}{dP} = \exp\left(\frac{1}{2}Y_T - \frac{1}{8}[Y]_T\right) = \exp\left(\frac{1}{2}X_T + \frac{1}{8}[X]_T\right).$$

The minimal entropy martingale measure Q^E for X is a martingale measure which minimizes the relative entropy with respect to P over all martingale measures for X . It can be characterized

as the martingale measure for X with finite relative entropy such that

$$\frac{dQ^E}{dP} = \exp\left(c + \int_0^T \eta_t dX_t\right),$$

where η is a predictable process with the property that $\int \eta dX$ is a Q -martingale for all martingale measures Q with finite relative entropy; see [11]. It follows from Corollary 5 that under mild conditions the measure H with density

$$\frac{dH}{dP} = \exp\left(c + \frac{1}{2}X_T\right)$$

is a martingale measure for X . The preceding discussion shows that typically, H is the minimal entropy martingale measure with $\eta = 1/2$. This is in general different from the minimal martingale measure; see [11, p. 1036]. Moreover, it is remarkable that $Q^E = H$ has such a simple form, which has consequences for the structure of conditionally symmetric martingales. In fact, for all $t \in [0, T]$ the measure H^t with density

$$\frac{dH^t}{dP} = \exp\left(c_t + \frac{1}{2}X_t\right) \quad (14)$$

is a martingale measure for X on $[0, t]$ but the normalizing constant c_t depends of course on t .

Definition 10. Let M be a continuous local martingale, and denote the right-continuous and complete filtration generated by M as \mathbb{F}^M . M is said to have the PRP (predictable representation property), if every \mathbb{F}^M -adapted local martingale N can be written as $N = N_0 + \int \vartheta dM$ for some predictable, M -integrable process ϑ .

Proposition 11. Let Y be a continuous P -martingale which is conditionally symmetric up to T and which has the PRP. Assume that $S = \mathcal{E}(Y)$ is a martingale, and that the minimal martingale measure \hat{P} exists for $X = Y - \frac{1}{2}[Y]$. Then Y is a Gaussian martingale.

Proof. By [19, Exercise VIII 1.27.], the fact that Y has the PRP under P implies that X has the PRP under \hat{P} . Moreover, the existence of \hat{P} implies the existence of the probability measures H^t as defined in (14) because

$$E\left[\exp\left(\frac{1}{2}X_t\right)\right] \leq E\left[\exp\left(\frac{1}{2}X_t + \frac{1}{8}[X]_t\right)\right] = E\left[E\left[\frac{d\hat{P}}{dP}\middle|\mathcal{F}_t\right]\right] = 1.$$

Since Y is conditionally symmetric up to T , it follows from Theorem 8 that S is conditionally self-dual, and hence, by Corollary 5, X is a conditionally symmetric martingale under each H^t . In particular, H^t is a martingale measure for X on $[0, t]$. The PRP implies by the second fundamental theorem of asset pricing, see Theorem 1.17 of [4], that $\hat{P} = H^t$ on \mathcal{F}_t which yields

$$\exp\left(\frac{1}{2}Y_t - \frac{1}{8}[Y]_t\right) = \exp\left(\frac{1}{2}X_t + \frac{1}{8}[X]_t\right) = \exp\left(c_t + \frac{1}{2}X_t\right),$$

for all $t \leq T$. It follows that $[Y] = [X]$ must be deterministic, and therefore Y is a Gaussian martingale. \square

The next result completely characterizes conditionally quasi self-dual continuous semimartingales in terms of conditional symmetry. In the case of non-vanishing α it is essentially a corollary to [22, Theorem 3.1].

Proposition 12. A continuous positive semimartingale S is conditionally quasi self-dual of non-vanishing order $\alpha = 1 - 2\kappa$, if and only if S^α is a martingale and $S = e^{\kappa[M]} \mathcal{E}(M)$ for a continuous conditionally symmetric local martingale M . For $\alpha = 0$ we assume in addition that $S = \exp(M)$ for an integrable process M . In that case, S is conditionally quasi self-dual of order zero if and only if M is a continuous conditionally symmetric martingale.

Proof. For $\alpha \neq 0$, S is conditionally quasi self-dual if and only if S^α is conditionally self-dual for some α , hence in particular a positive continuous martingale. We can then write by Theorem 8

$$S^\alpha = \mathcal{E}(\alpha M) = \exp\left(\alpha M - \frac{1}{2}\alpha^2 [M]\right) = e^{\alpha\kappa[M]} \mathcal{E}(M)^\alpha$$

for some conditionally symmetric local martingale M . On the other hand, if $S = e^{\kappa[M]} \mathcal{E}(M)$, we have

$$S^\alpha = e^{\alpha\kappa[M]} \mathcal{E}(M)^\alpha = \exp\left(\alpha M + \left(\kappa - \frac{1}{2}\right)\alpha [M]\right).$$

Since S^α is a positive martingale it follows that $S^\alpha = \mathcal{E}(N)$ for a continuous local martingale N . The uniqueness of the canonical semimartingale decomposition implies $N = \alpha M$ which implies that

$$\left(\kappa - \frac{1}{2}\right)\alpha = -\frac{1}{2}\alpha^2.$$

In the case when $\alpha \neq 0$, dividing by α yields the result. If $\alpha = 0$, we start by assuming that S is conditionally quasi self-dual of order $\alpha = 0$. For an arbitrary non-negative Borel function f , define $g = f \circ \log$. By assumption we have for any stopping time $\tau \in [0, T]$

$$\begin{aligned} E[f(M_T - M_\tau) | \mathcal{F}_\tau] &= E[g(\exp(M_T - M_\tau)) | \mathcal{F}_\tau] \\ &= E[g(\exp(M_\tau - M_T)) | \mathcal{F}_\tau] = E[f(M_\tau - M_T) | \mathcal{F}_\tau], \end{aligned}$$

for an arbitrary non-negative Borel function f , i.e. M is conditionally symmetric combined with the integrability assumption, also a martingale, and it is clearly continuous. Furthermore, $S = \exp(M) = e^{\frac{1}{2}[M]} \mathcal{E}(M)$ holds.

Conversely, if $M = \log(S)$ is a continuous conditionally symmetric martingale, then for all non-negative Borel functions f define $g = f \circ \exp$ so that

$$\begin{aligned} E(f(\exp(M_T - M_\tau)) | \mathcal{F}_\tau) &= E(g(M_T - M_\tau) | \mathcal{F}_\tau) \\ &= E(g(M_\tau - M_T) | \mathcal{F}_\tau) \\ &= E(f(\exp(M_\tau - M_T)) | \mathcal{F}_\tau), \end{aligned}$$

which implies the conditional quasi self-duality of order zero. \square

Example 13 (Geometric Brownian Motion). The results presented lead to the following view of the symmetries of geometric Brownian motion. Let $Y = \sigma W$ for a standard Brownian motion W and $\sigma > 0$. Since Y is a continuous conditionally symmetric martingale, Theorem 8 yields that

$$\mathcal{E}(Y) = \exp\left(Y - \frac{1}{2}[Y]\right) = \exp\left(\sigma W - \frac{1}{2}\sigma^2 t\right)$$

is a conditionally self-dual process. Denoting by λ a shift parameter, we consider the process

$$S = \exp\left(\sigma W - \frac{1}{2}\sigma^2 t + \lambda t\right) = \exp(\kappa[Y]) \mathcal{E}(Y), \quad \text{where } \kappa = \frac{\lambda}{\sigma^2}.$$

By Proposition 12 S is conditionally quasi self-dual of order zero if and only if $\lambda = \frac{1}{2}\sigma^2$ (since we have the ordinary exponent of a continuous conditionally symmetric martingale) and, in view of the fact that S^α , $\alpha = 1 - 2\kappa = 1 - \frac{2\lambda}{\sigma^2}$, is a martingale, it is conditionally quasi self-dual of order α ; cf. e.g. [2,3].

4. Ocone martingales and strong self-duality

In this section we discuss a connection between Ocone martingales and a strong version of self-duality of their associated stochastic exponentials, as motivated by the discussion in [22]. However, the previously introduced conditional notions of symmetry resp. self-duality are not quite fitting for such a discussion as Ocone martingales in particular enjoy a stronger notion of symmetry.

Definition 14. Let M be a continuous P -martingale vanishing at zero such that $[M]_\infty = \infty$, and consider its Dambis–Dubins–Schwartz (DDS) representation $M = B_{[M]}$. The process M is called an *Ocone martingale* if B and $[M]$ are independent.

It has been proved in [23] that if a martingale is Ocone and has the PRP, then it is Gaussian. A more interesting example of an Ocone martingale is given by the solution of the stochastic differential equation

$$\begin{aligned} dM_t &= V_t dB_t, \\ dV_t &= -\mu V_t dt + \sqrt{V_t} dW_t, \end{aligned}$$

where $\mu > 0$ and B, W are two independent Brownian motions. This follows by [1, Chapter 2, Theorem 2.6], since $[M] = \int V^2 dt$ is independent of B . Moreover, Lévy's stochastic area process is also an Ocone martingale; see [23].

Definition 15. An adapted process X is process symmetric if $X \sim -X$ (i.e. the finite dimensional distributions of X and $-X$ are the same). In particular, for semimartingales X with $X_0 = 0$ this is equivalent to

$$E \left[\exp \left(i \int_0^T \theta_t dX_t \right) \right] = E \left[\exp \left(-i \int_0^T \theta_t dX_t \right) \right] \quad \forall \theta \in \mathcal{S},$$

where \mathcal{S} denotes the space of deterministic and bounded Borel functions on $[0, T]$.

Remark 16. Ocone martingales are always process symmetric; see Tehranchi [22].

It is important to stress that different symmetry concepts are not equivalent. Since for example conditional symmetry implies the martingale property for integrable processes, we have that an integrable process symmetric X which is not a martingale cannot be conditionally symmetric. For example, if Z is a symmetric integrable random variable, then the process $(Zt)_{t \in [0, T]}$ is still process symmetric but not a martingale. Less obvious is that there are also process symmetric martingales which are not conditionally symmetric.

Example 17. (i) The martingale $M = \int B^2 dB$ is process symmetric since

$$-\int B^2 dB = \int (-B)^2 d(-B).$$

Since

$$B = \int \left(\frac{d[M]}{dt} \right)^{-\frac{1}{2}} dM,$$

we have that the Brownian filtration $\mathbb{F} = (\mathcal{F}_t)$ equals the filtration \mathbb{F}^M generated by M . Moreover, M has the PRP, but is non-Gaussian, and hence not Ocone.

- (ii) It is worth noting, in light of Theorem 22, that the stochastic exponential $\mathcal{E}(M)$ is a strict local martingale. This follows e.g. by Corollary 2.2 of [14] since the with M associated auxiliary diffusion

$$d\tilde{Y}_t = \tilde{Y}_t^2 dt + dB_t$$

does explode.

- (iii) However, M is not conditionally symmetric. Choose $0 < t < T$ and assume by means of contradiction that M is conditionally symmetric. In particular,

$$E[(M_T - M_t)^3 | \mathcal{F}_t] = E[(M_t - M_T)^3 | \mathcal{F}_t],$$

since the symmetry is satisfied by the positive and the negative part of the third conditional moment, so that

$$E[(M_T - M_t)^3 | \mathcal{F}_t] = 0$$

holds a.s., where we have used that $E[|M_T - M_t|^3] < \infty$. However, noting that $W_s = B_{t+s} - B_t$ defines a Brownian motion independent of \mathcal{F}_t and that B_t is \mathcal{F}_t -measurable, we can write

$$M_T - M_t = \int_0^{T-t} W_s dW_s + B_t^2 W_{T-t} + B_t(W_{T-t}^2 - (T-t)).$$

By a straightforward but lengthy calculation, the third conditional moment of this martingale increment can, for $t < T$, be written as a nontrivial polynomial in B_t , which, for $t > 0$, will not take a.s. only values in the roots of the polynomial, i.e. we end up with a contradiction.

It is observed by Tehranchi [22] that continuous Ocone martingales are conditionally symmetric with respect to deterministic times. The next result shows that this is still true for bounded stopping times.

Lemma 18. *A continuous Ocone martingale M with natural filtration $\mathbb{F} = (\mathcal{F}_t)$ is conditionally symmetric.*

Proof. Since M is Ocone we have $M = \beta_{[M]}$ for a Brownian motion β (with natural filtration $\mathbb{B} = (\mathcal{B}_t)$) being independent of $[M]$. Denote by $\mathbb{G} = (\mathcal{G}_t)$ the right-continuous enlargement of the filtration $\mathcal{B}_t \vee \sigma([M])$. Following [5, p. 129] we have that for τ being an \mathbb{F} -stopping time it follows that $[M]_\tau$ is a \mathbb{G} -stopping time. Indeed, by denoting $A_t = \inf\{s : [M]_s > t\}$ we have

$$\{[M]_\tau \leq t\} = \{\tau \leq A_t\} \in \mathcal{F}_{A_t} \subset \bigcap_{\varepsilon > 0} \sigma(M^{A_t+\varepsilon}) \subset \bigcap_{\varepsilon > 0} [\mathcal{B}_{t+\varepsilon} \vee \sigma([M])] = \mathcal{G}_t,$$

where in our case $\tau \leq T < \infty$ and $[M]$ is continuous, so that we end up with a finite stopping time. As in the proof of Lemma 2 on p. 129 in [5] the Ocone property and lemma 1 on p. 129 in [5] imply that β is a \mathbb{G} -Brownian motion. By [12, Theorem 13.11] $\beta'_u = \beta_{u+[M]_\tau} - \beta_{[M]_\tau}$ is a

Brownian motion independent of $\mathcal{G}_{[M]_\tau}$. Hence, for $\tau \leq T < \infty$ we have for any non-negative Borel function f

$$\begin{aligned} E[f(M_T - M_\tau) | \mathcal{F}_\tau] &= E[E[f(\beta_{[M]_T} - \beta_{[M]_\tau}) | \mathcal{G}_{[M]_\tau}] | \mathcal{F}_\tau] \\ &= E[E[f(\beta_{[M]_\tau} - \beta_{[M]_T}) | \mathcal{G}_{[M]_\tau}] | \mathcal{F}_\tau] = E[f(M_\tau - M_T) | \mathcal{F}_\tau], \end{aligned}$$

so that M is conditionally symmetric. \square

We assume w.l.o.g. that $S_0 = 1$ and set $S = \exp(X) = \mathcal{E}(Y)$ where X (and then Y) is a continuous semimartingale.

Recall that \mathcal{S} is the space of deterministic and bounded Borel functions on $[0, T]$. For $\phi \in \mathcal{S}$, we set $X^\phi = \int \phi dY - \frac{1}{2} \int \phi^2 d[Y]$, and $S^\phi := \exp(X^\phi) = \mathcal{E}(\int \phi dY)$. In the case that all S^ϕ are martingales, we define dual probability measures Q^ϕ via

$$\frac{dQ^\phi}{dP} = S_T^\phi.$$

Definition 19. We say that $S = \mathcal{E}(Y)$, for a continuous martingale Y , is strongly self-dual if for all $\phi \in \mathcal{S}$, the S^ϕ are martingales and that with equality in distribution as a process living on $[0, T]$,

$$\{S^\phi, P\} \sim \left\{ \frac{1}{S^\phi}, Q^\phi \right\}.$$

In the case when S is strongly self-dual then, by choosing $\phi = 1$, it also implies an unconditional form of the self-duality property known as put-call symmetry, which is the most frequently used definition in the previous literature.

Lemma 20. S is strongly self-dual if and only if for all $\phi \in \mathcal{S}$, the S^ϕ are martingales and

$$\{X^\phi, P\} \sim \{-X^\phi, Q^\phi\}. \quad (15)$$

Proof. Note that the martingale assumptions are the same. Assume that S is strongly self-dual. For an arbitrary non-negative functional F define G via

$$G := F \circ \log.$$

Then

$$\begin{aligned} E_P[F(X_t^\phi, 0 \leq t \leq T)] &= E_P[G(S_t^\phi, 0 \leq t \leq T)] = E_{Q^\phi} \left[G \left(\frac{1}{S_t^\phi}, 0 \leq t \leq T \right) \right] \\ &= E_{Q^\phi} [F(-X_t^\phi, 0 \leq t \leq T)], \end{aligned}$$

so that (15) follows. The converse direction follows similarly. \square

For the record, we state the next proposition which is analogous to Corollary 5. If for $\phi \in \mathcal{S}$, $\exp(X^\phi)$ is a P -martingale, then

$$c_\phi = E \left[\exp \left(\frac{1}{2} X_T^\phi \right) \right] < \infty,$$

so we can define probability measures H^ϕ (analogous to the half measure H) via

$$\frac{dH^\phi}{dP} = c_\phi^{-1} \exp\left(\frac{1}{2}X_T^\phi\right).$$

Proposition 21. *S is strongly self-dual if and only if for all $\phi \in \mathcal{S}$ we have that the S^ϕ are martingales and the X^ϕ are process symmetric under the measures H^ϕ .*

Proof. The strong self-duality implies the martingale assumptions and with Lemma 20 it implies for arbitrary $\lambda, \phi \in \mathcal{S}$ that

$$\begin{aligned} c_\phi^{-1} E_P \left[\exp\left(\frac{1}{2}X_T^\phi + i \int_0^T \lambda_t dX_t^\phi\right) \right] \\ = c_\phi^{-1} E_{Q^\phi} \left[\exp\left(\frac{1}{2}(-X_T^\phi) + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right], \end{aligned}$$

while from the definitions of H^ϕ and Q^ϕ

$$E_{H^\phi} \left[\exp\left(i \int_0^T \lambda_t dX_t^\phi\right) \right] = c_\phi^{-1} E_P \left[\exp\left(\frac{1}{2}X_T^\phi + i \int_0^T \lambda_t dX_t^\phi\right) \right]$$

and

$$\begin{aligned} E_{H^\phi} \left[\exp\left(-i \int_0^T \lambda_t dX_t^\phi\right) \right] &= c_\phi^{-1} E_P \left[\exp\left(\frac{1}{2}X_T^\phi + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right] \\ &= c_\phi^{-1} E_{Q^\phi} \left[\exp\left(\frac{1}{2}(-X_T^\phi) + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right]. \end{aligned}$$

Since λ and ϕ were arbitrarily chosen, we end up with the process symmetries of the processes X^ϕ under H^ϕ .

Conversely, the process symmetries imply for arbitrary λ (and $\phi \in \mathcal{S}$) that

$$\begin{aligned} c_\phi E_{H^\phi} \left[\exp\left(-\frac{1}{2}X_T^\phi + i \int_0^T \lambda_t dX_t^\phi\right) \right] \\ = c_\phi E_{H^\phi} \left[\exp\left(-\frac{1}{2}(-X_T^\phi) + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right], \end{aligned}$$

while again by the definitions of H^ϕ and Q^ϕ

$$E_P \left[\exp\left(i \int_0^T \lambda_t dX_t^\phi\right) \right] = c_\phi E_{H^\phi} \left[\exp\left(-\frac{1}{2}X_T^\phi + i \int_0^T \lambda_t dX_t^\phi\right) \right]$$

and

$$\begin{aligned} E_{Q^\phi} \left[\exp\left(-i \int_0^T \lambda_t dX_t^\phi\right) \right] &= E_P \left[\exp\left(X_T^\phi + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right] \\ &= c_\phi E_{H^\phi} \left[\exp\left(-\frac{1}{2}(-X_T^\phi) + i \int_0^T \lambda_t d(-X_t^\phi)\right) \right]. \end{aligned}$$

Hence, in view of the imposed martingale assumptions, the strong self-duality now follows by Lemma 20. \square

In the following result we show that the Ocone property translates one-to-one via lifting by stochastic exponentiation into the strong self-duality property.

Theorem 22. A continuous martingale Y is an Ocone martingale if and only if $\mathcal{E}(Y)$ is strongly self-dual.

Proof. Let first Y be a continuous Ocone martingale, and set for $\phi \in \mathcal{S}$

$$\tilde{Y} = Y - \int \phi d[Y].$$

Here we suppress the dependency of \tilde{Y} on ϕ for ease of notation.

By Theorem 1 and Comment 2 of Vostrikova and Yor [23], it holds that Y is a continuous Ocone martingale if and only if

(i) For all $\phi \in \mathcal{S}$,

$$\{Y, P\} \sim \{\tilde{Y}, Q^\phi\}, \quad (16)$$

or equivalently,

$$\{[Y], P\} \sim \{[Y], Q^\phi\}; \quad (17)$$

note that $[Y] = [\tilde{Y}]$.

(ii) $\mathcal{E}(\int \phi dY)$ is a martingale for all $\phi \in \mathcal{S}$.

We now show that $\{X^\phi, P\} \sim \{-X^\phi, Q^\phi\}$ for all $\phi \in \mathcal{S}$, which implies (in view of (ii)) by Lemma 20 strong self-duality of $S = \mathcal{E}(Y)$. First note that \tilde{Y} under Q^ϕ is also Ocone and thus, in particular process symmetric. Furthermore, we have for all $\lambda, \psi \in \mathcal{S}$ by the aforementioned properties of Ocone martingales, cf. also Lemma 2.5 of [17], that

$$\begin{aligned} & E \left[\exp \left(i \int_0^T \lambda_t dX_t^\phi \right) \right] \\ &= E \left[\exp \left(i \int_0^T \lambda_t d \left(\int_0^t \phi_s dY_s - \frac{1}{2} \int_0^t \phi_s^2 d[Y]_s \right) \right) \right] \\ &= E_{Q^\phi} \left[\exp \left(i \int_0^T \lambda_t d \left(\int_0^t \phi_s d\tilde{Y}_s - \frac{1}{2} \int_0^t \phi_s^2 d[\tilde{Y}]_s \right) \right) \right] \\ &= E_{Q^\phi} \left[\exp \left(i \int_0^T \lambda_t d \left(\int_0^t \phi_s d(-\tilde{Y}_s) - \frac{1}{2} \int_0^t \phi_s^2 d[\tilde{Y}]_s \right) \right) \right] \\ &= E_{Q^\phi} \left[\exp \left(i \int_0^T \lambda_t d \left(- \left(\int_0^t \phi_s dY_s - \int_0^t \phi_s^2 d[Y]_s + \frac{1}{2} \int_0^t \phi_s^2 d[Y]_s \right) \right) \right) \right] \\ &= E_{Q^\phi} \left[\exp \left(i \int_0^T \lambda_t d \left(- \left(\int_0^t \phi_s dY_s - \frac{1}{2} \int_0^t \phi_s^2 d[Y]_s \right) \right) \right) \right] \\ &= E_{Q^\phi} \left[\exp \left(-i \int_0^T \lambda_t dX_t^\phi \right) \right] \end{aligned}$$

which proves the claim and hence the first implication.

As for the other direction, we will show property (17) for all $\phi \in \mathcal{S}$. Let $\mathcal{E}(\int \phi dY) = \exp(X^\phi)$ where $X^\phi = \int \phi dY - \frac{1}{2} \int \phi^2 d[Y]$, and define probability measures Q^ϕ via

$$dQ^\phi/dP = \mathcal{E} \left(\int \phi dY \right)_T = \exp(X_T^\phi).$$

We assume first that ϕ is bounded away from zero, and that Y is a square-integrable martingale, i.e. $E[Y_t^2] < \infty$ for all $t \geq 0$. Note that $[X^\phi] = \int \phi^2 d[Y]$ and therefore $[Y] = \int \phi^{-2} d[X^\phi]$. We have for every non-negative functional F , with $F(U)$ denoting $F(U_t; 0 \leq t \leq T)$ for any stochastic process U ,

$$E_{Q^\phi}[F([Y])] = E_P\left[\exp\left(X_T^\phi\right) F\left(\int \phi^{-2} d[X^\phi]\right)\right] = E_{Q^\phi}\left[F\left(\int \phi^{-2} d[X^\phi]\right)\right].$$

On the other hand,

$$E_P[F([Y])] = E_P\left[F\left(\int \phi^{-2} d[X^\phi]\right)\right].$$

Hence the strong self-duality of S implies by Lemma 20 that $[Y]$ under Q^ϕ has the same law as $[Y]$ under P , for all $\phi \in \mathcal{S}$ which are bounded away from zero. Equivalently, for all such ϕ ; $N \in \mathbb{N}$ arbitrary; $0 \leq t_1 \leq \dots \leq t_N \leq T$; and arbitrary $u = (u_1, \dots, u_N) \in \mathbb{R}^N$ we set

$$\Psi(u) = \exp\left(i\left(u_1[Y]_{t_1} + \dots + u_N[Y]_{t_N}\right)\right),$$

and have that

$$\begin{aligned} E\left[\Psi(u) \exp\left(\int_0^T \phi_t dY_t - \frac{1}{2} \int_0^T \phi_t^2 d[Y]_t\right)\right] &= E_{Q^\phi}[\Psi(u)] \\ &= E[\Psi(u)]. \end{aligned} \quad (18)$$

Let now $\phi \in \mathcal{S}$ be arbitrary, i.e., in particular ϕ may vanish on a set $\Gamma \subset [0, T]$. We denote by $\phi^{(n)} \in \mathcal{S}$ functions which coincide with ϕ as long as $|\phi_t| \geq 1/n$, and which equal $1/n$ if $|\phi_t| \leq 1/n$, so that $\phi^{(n)} \rightarrow \phi$ pointwise. By dominated convergence for stochastic integrals (see [19, Theorem IV.2.12]), it follows that in probability,

$$U_n := \mathcal{E}\left(\int \phi^{(n)} dY\right)_T \rightarrow \mathcal{E}\left(\int \phi dY\right)_T.$$

We will now show that the family $\{U_n\}_{n \in \mathbb{N}}$ is uniformly integrable. For this, it suffices to show that

$$\sup_n E[U_n \log(U_n)] < \infty.$$

Indeed, using that so far Y was assumed to be a square-integrable martingale, and therefore $E[Y_t] < \infty$ for all $t \geq 0$ (see [18, Corollary II.6.3]),

$$\begin{aligned} E[U_n \log(U_n)] &= E_{Q^{\phi^{(n)}}}\left[\int_0^T \phi_t^{(n)} dY_t - \frac{1}{2} \int_0^T (\phi_t^{(n)})^2 d[Y]_t\right] \\ &= E_{Q^{\phi^{(n)}}}\left[\int_0^T \phi_t^{(n)} dY_t - \int_0^T (\phi_t^{(n)})^2 d[Y]_t + \frac{1}{2} \int_0^T (\phi_t^{(n)})^2 d[Y]_t\right] \\ &= E_{Q^{\phi^{(n)}}}\left[\frac{1}{2} \int_0^T (\phi_t^{(n)})^2 d[Y]_t\right] \\ &= E\left[\frac{1}{2} \int_0^T (\phi_t^{(n)})^2 d[Y]_t\right], \end{aligned}$$

since by what has already been proved, $[Y]$ has the same distribution under both $Q^{\phi^{(n)}}$ and P since the $\phi^{(n)}$ are bounded away from zero. We have, since Y was assumed to be square-integrable,

$$E \left[\frac{1}{2} \int_0^T \left(\phi_t^{(n)} \right)^2 d[Y]_t \right] \leq \text{const.} E [[Y]_T] < \infty.$$

Hence the U_n are uniformly integrable, and we conclude by (18) that

$$\begin{aligned} E \left[\Psi(u) \exp \left(\int_0^T \phi_t dY_t - \frac{1}{2} \int_0^T \phi_t^2 d[Y]_t \right) \right] \\ = \lim_n E \left[\Psi(u) \exp \left(\int_0^T \phi_t^{(n)} dY_t - \frac{1}{2} \int_0^T \left(\phi_t^{(n)} \right)^2 d[Y]_t \right) \right] \\ = E [\Psi(u)]. \end{aligned}$$

Therefore $[Y]$ has the same distribution under both Q^ϕ and P for all $\phi \in \mathcal{S}$. It follows by the aforementioned result of [23] that Y is an Ocone martingale.

In the case that Y is a continuous martingale, not necessarily square-integrable, the result follows by localization: there is an increasing sequence of stopping times (T_n) such that Y^{T_n} is bounded, e.g. $T_n = \inf \{t : |Y_t| = n\}$. Therefore the previous result applies on $[0, T_n]$, each n . Letting n tend to infinity yields then the general result. \square

This result should be seen in the context of Tehranchi's [22] Theorem as given in Theorem 8. In both results, a certain symmetry property (conditional respectively Ocone symmetry) translates into a self-duality property (conditional respectively strong) of the associated stochastic exponential. The structure of the proofs, however, is completely different. While Tehranchi's proof rests on his characterization that for a continuous local martingale Y conditional symmetry is equivalent to the property that Y_T given $\mathcal{F}_t \vee \sigma([Y]_T)$ is normally distributed with expectation Y_t and variance $[Y]_T - [Y]_t$ for all $0 \leq t \leq T$, we work with properties of Ocone martingales as developed in [17,23].

The notion of strong self-duality is justified by an economic interpretation, namely that the distribution of the price process S^ϕ for arbitrary parameter function $\phi \in \mathcal{S}$ remains invariant under the dual market transformation. Furthermore, it is shown in Theorem 22 that it is equivalent to the Ocone property of its stochastic logarithm.

The relationship between conditional and strong self-duality is however beyond the scope of this paper, since this amounts to the at present open conjecture by Tehranchi whether there exists any non-Ocone conditionally symmetric martingale. To emphasize it once more, the stochastic logarithm of a continuous positive strongly self-dual martingale is Ocone (see Theorem 22), while the stochastic logarithm of a continuous positive conditionally self-dual martingale is conditionally symmetric (see Theorem 8). Hence finding a counter-example to Tehranchi's conjecture would show that the two notions of self-duality are different, whereas if the conjecture were true, the two notions would in fact amount to the same. In the latter case it would be still interesting to note that the two proofs are vastly different. Regarding duality relations between exotic options, the notion of strong duality seems to be the appropriate concept; see [20].

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References

- [1] E. Barndorff-Nielsen, A. Shiryaev, *Change of Time and Change of Measure*, World Scientific, Singapore, 2010.
- [2] P. Carr, A. Chou, Breaking barriers, *Risk* 10 (9) (1997) 139–145.
- [3] P. Carr, R. Lee, Put-call symmetry: extensions and applications, *Mathematical Finance* 19 (2009) 523–560.
- [4] A.S. Cerny, A.N. Shiryaev, Vector stochastic integrals and the fundamental theorems of asset pricing, *Proceedings of the Steklov Institute of Mathematics* 237 (2002) 6–49.
- [5] L.E. Dubins, M. Émery, M. Yor, On the Lévy transformation of Brownian motions and continuous martingales, in: *Séminaire de Probabilités (Strasbourg)*, Springer, Berlin, 1993, pp. 122–132.
- [6] E. Eberlein, A. Papapantoleon, A.N. Shiryaev, On the duality principle in option pricing: semimartingale setting, *Finance & Stochastics* 12 (2008) 265–292.
- [7] E. Eberlein, A. Papapantoleon, A.N. Shiryaev, Esscher transform and the duality principle for multidimensional semimartingales, *The Annals of Applied Probability* 19 (2009) 1944–1971.
- [8] N. El Karoui, M. Jeanblanc, Options exotiques, *Finance* 20 (1999) 49–67.
- [9] J. Fajardo, E. Mordecki, Symmetry and duality in Lévy markets, *Quantitative Finance* 6 (3) (2006) 219–227.
- [10] J. Fajardo, E. Mordecki, Market symmetry in time-changed Brownian models, *Finance Research Letters* 7 (1) (2010) 53–59.
- [11] P. Grandits, T. Rheinländer, On the minimal entropy martingale measure, *Annals of Probability* 30 (2002) 1003–1038.
- [12] O. Kallenberg, *Foundations of Modern Probability*, second ed., Springer, New York, 2002.
- [13] N. Kazamaki, Continuous Exponential Martingales and BMO, in: *LNLM*, vol. 1579, Springer, Berlin, 1994.
- [14] A. Mijatović, M. Urusov, On the martingale property of certain local martingales, *Probability Theory and Related Fields* (2010). Online First.
- [15] I. Molchanov, M. Schmutz, Multivariate extension of put-call symmetry, *SIAM Journal of Financial Mathematics* 1 (2010) 398–426.
- [16] I. Molchanov, M. Schmutz, Exchangeability-type properties of asset prices, *Advances in Applied Probability* 43 (2011) 666–687.
- [17] D.L. Ocone, A symmetry characterization of conditionally independent increment martingales, in: D. Nualart, M. Sanz (Eds.), *Proceedings of the San Felice Workshop on Stochastic Analysis*, Birkhäuser, 1993.
- [18] P. Protter, *Stochastic Integration and Differential Equations*, second ed., Springer, Berlin, 2005, version 2.1.
- [19] D. Revuz, M. Yor, *Continuous Martingales and Brownian Motion*, third ed., Springer, Berlin, 1998.
- [20] T. Rheinländer, J. Sexton, Reflection property for Ocone martingales, Working Paper, TU Vienna, 2012.
- [21] M. Schweizer, On the minimal martingale measure and the Föllmer-Schweizer decomposition, *Stochastic Analysis and Applications* 13 (1995) 573–599.
- [22] M. Tehranchi, Symmetric martingales and symmetric smiles, *Stochastic Processes and their Applications* 119 (2009) 3785–3797.
- [23] L. Vostrikova, M. Yor, Some invariance properties of Ocone’s martingales, in: *Séminaire de Probabilités*, Vol. XXXIV, in: *LNLM*, Springer, Berlin, 2000, pp. 417–431.