A simplified unified propagator model for signed/unsigned order flow, concave price impact and rough volatility

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Abstract

We simplify the setup in [MORS26] by exogenously modelling the signed order flow as an fBM-type process with $H > \frac{1}{2}$, which avoids the need for Hawkes processes, Mittag-Leffler functions and lengthy scaling limit arguments.

0.1 Positive order flow and the inversion formula

Similar to Theorem 3.1 in [MORS26][1], we consider a hyper-rough Heston process $(F_t^+)_{t\geq 0}$ for cumulative positive order flow which satisfies

$$F_t^+ \;=\; g(t) + \int_0^t f(t-s) B_{F_s^+} ds$$

where B is a standard Brownian motion with $B_0 = 0$ and $f(t) = e^{-\theta t} t^{H-\frac{1}{2}}$ is the usual Gamma kernel with $H \in (-\frac{1}{2}, \frac{1}{2})$, $\theta > 0$ so $f \in L^1$ and we assume $g \in C^1$. F_t^+ is a.s. $(2\alpha - \varepsilon) \wedge 1$-Hölder continuous where $\alpha = H + \frac{1}{2}$ (see e.g. Theorem 3.1 in [JM20] for details) [2] and F^+ is an increasing process which is non-differentiable if $H \leq 0$. Then if $h * f \equiv 1$, we have the inversion formula:

$$\begin{aligned}
\int_0^t h(t-s)(F_s^+ - g(s))ds \;=\; \int_0^t h(t-s)\int_0^s f(s-u) B_{F_u^+} du ds \;&=\; \int_0^t \int_u^t h(t-s) f(s-u) ds B_{F_u^+} du \\
&=\; \int_0^t \int_0^{t-u} h(t-s-u) f(s) ds B_{F_u^+} du \\
&=\; \int_0^t (h*f)(t-u) B_{F_u^+} du \;=\; \int_0^t B_{F_u^+} du
\end{aligned}$$

(where Fubini is justified since $F_t^+ < \infty$ a.s. for finite t and B is a.s. continuous), and hence

$$\frac{d}{dt}\int_0^t h(t-s)(F_s^+ - g(s))ds \;=\; B_{F_t^+} \tag{1}$$

Lebesgue a.e. Taking Laplace transforms, the condition $h * f \equiv 1$ becomes $\hat{f}(\lambda)\hat{h}(\lambda) = \frac{1}{\lambda}$, from which we find that

$$h(t) \;=\; \frac{\theta^\alpha}{\Gamma(\alpha)}\Big(1 - \frac{\Gamma(-\alpha, t\theta)}{\Gamma(-\alpha)}\Big)$$

where $\Gamma(a,z) = \int_z^\infty s^{a-1} e^{-s} ds$ is the incomplete Gamma function, and in particular $h(t) = O(t^{-H-\frac{1}{2}})$ as $t \to 0$.

0.2 Persistent signed order flow

Again following [MORS26], we now assume the *signed* order flow for an asset is

$$V_t \;=\; F_t^+ - F_t^-$$

where $F_t^- = g(t) + \int_0^t f(t-s) W_{F_s^-} ds$ and W is another Brownian motion independent of B (so F^- is an i.i.d. copy of F^+). Then we see that

$$\frac{d}{dt}\int_0^t h(t-s) V_s ds \;=\; B_{F_t^+} - W_{F_t^-}$$

since the g terms cancel, and for $0 \leq t \leq u$ we have

$$\mathbb{E}(F_u^+ | \mathcal{F}^B_{F_t^+}) \;=\; g(u) + \mathbb{E}\Big(\int_0^u f(u-s) B_{F_s^+} ds \,|\, \mathcal{G}_t^+\Big) \;=\; g(u) + \int_0^t f(u-s) B_{F_s^+} ds + B_{F_t^+}\int_t^u f(u-s) ds$$

(and similarly for $\mathbb{E}(F_u^- | \mathcal{F}^W_{F_t^-})$), where $\mathcal{G}_t^+ = \mathcal{F}^B_{F_t^+}$, assuming $(B_{F_t^+})_{t\geq 0}$ is a $\mathcal{G}_t^+-$martingale (see e.g. Section 7 in [AJ21] for more on this).

[1] see also section 5.4 in [FGS21]

[2] we can simulate F^+ using the Monte Carlo scheme in [AA25] using Normal Inverse Gaussian variates

0.3 Price dynamics and the propagator model

Making the usual assumption that the asset price $P_t = \kappa \lim_{u\to\infty} \mathbb{E}(F_u|\mathcal{G}_t)$ where $F_t = F_t^+ - F_t^-$ and $\mathcal{G}_t = \sigma(\mathcal{G}_t^+, \mathcal{G}_t^-)$ with $\mathcal{G}_t^- = \mathcal{F}^W_{F_t^-}$ (for some $\kappa > 0$)[3], we find that $f(u-s) \to 0$ as $u \to \infty$ since $\theta > 0$, but $\lim_{u\to\infty} \int_t^u f(u-s)ds = c_{H,\theta}$ where $c_{H,\theta} = \theta^{-\frac{1}{2}-H}\Gamma(\frac{1}{2}+H)$, so

$$P_t \;=\; \kappa \lim_{u\to\infty} \mathbb{E}(F_u^+ - F_u^- \,|\, \sigma(\mathcal{F}^B_{F_t^+}, \mathcal{F}^W_{F_t^-})) \;=\; \kappa\, c_{H,\theta}(B_{F_t^+} - W_{F_t^-})$$

i.e. P is the difference of two i.i.d. hyper-rough Heston models (each with correlation $\rho = 1$ since each process only has one driving Brownian motion), and

$$P_t \;=\; \kappa\, c_{H,\theta}\, \frac{d}{dt}\int_0^t h(t-s)V_s ds$$

which is a weak formulation of the usual Propagator model, and the *unsigned* order flow is $U_t = F_t^+ + F_t^-$.

0.4 Power-law price impact

In particular, the *market impact function* of an exogenous metaorder executed at constant trading speed 1 up to time t_0 is given by

$$MI(t) \;=\; \frac{d}{dt}\int_0^t h(t-s)sds \;=\; \frac{\theta^{-\alpha_-}(t\theta\Gamma(-\alpha) - t\theta\Gamma(-\alpha,t\theta) - \Gamma(\alpha_-,0) + \Gamma(\alpha_-,t\theta))}{\Gamma(-\alpha)\Gamma(\alpha)}$$

for $0 \le t < t_0$ (where $\alpha_- = \frac{1}{2} - H$) for $0 \le t \le t_0$ which is $O(t^{\frac{1}{2}-H})$ as $t \to 0$ and globally concave in t for $H \in (-\frac{1}{2}, \frac{1}{2})$, consistent with empirical evidence (note the usual square-root impact law corresponds to $H = 0$ here), and we can show that the asymptotic (i.e. permanent) impact as $t \to \infty$ (given no trading after t_0) is

$$MI(\infty) \;=\; \frac{t_0\theta^{\alpha}}{\Gamma(\frac{1}{2}+H)}$$

(this is the asymptotic grey line in the plot below). For $H = \frac{1}{2}$, $h(t) = \theta$ which corresponds to pure permanent price impact; conversely $\lim_{\theta\to 0} h(t) = const. \times t^{-\frac{1}{2}-H}$. Recall from above that F_t^+ has Hölder regularity $(2\alpha - \varepsilon) \wedge 1$, and empirical evidence in [MORS26] suggests that $2\alpha \in (\frac{1}{2}, 1)$ which corresponds to $H \in (-\frac{1}{4}, 0)$.

0.5 Extensions

If we consider a mixed model where $f(t) = e^{-\theta t}t^{H-\frac{1}{2}} + e^{-\theta_2 t}t^{H_2-\frac{1}{2}}$ with $H \in (-\frac{1}{4}, 0)$ and $H_2 \in (0, \frac{1}{2})$, then we find that

$$h(t) \;=\; \frac{1}{\Gamma(\alpha)}\sum_{n=0}^{\infty}(-c)^n \sum_{k=0}^{\infty}\frac{(\beta n)_k}{k!}\,\delta^k\,\theta^{-(\mu_n+k)}\,\frac{\gamma(\mu_n+k,\theta t)}{\Gamma(\mu_n+k)}$$

where $\beta = \frac{1}{2} + H_2$, $c = \Gamma(\beta)/\Gamma(\alpha)$, $\Delta = \theta - \theta_2$, $\mu_n = \beta n - \alpha(n+1)$, $\gamma(a,z) = \int_0^z s^{a-1}e^{-s}ds$ is the lower incomplete Gamma function and $(a)_k$ denotes the Pochammer symbol. We can then use two (possibly different) f functions to drive $F^{\pm}$, and the presence of the positive H_2 parameter means the price dynamics will now have a (non-hyper) rough component, which is arguably more realistic. We can have W and B correlated which gives greater flexibility in capturing skew for the price process P_t.

[3] note we are assuming $P_0 = 0$ without loss of generality since we can easily add a P_0 term

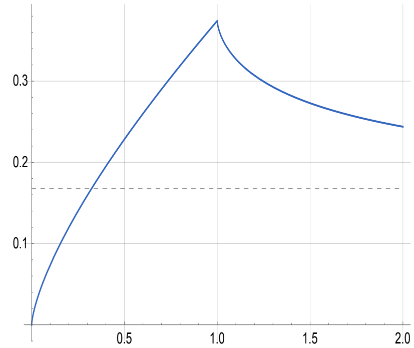

Figure 1: Concave price impact of an exogenous metaorder executed at constant trading speed 1 over $[0,1]$ with $H=-0.2$, $\theta=0.1$ and $\kappa=1$. The blue line asymptotes to the constant level $MI(\infty)$ (grey line) as $t\to\infty$ which represents the asymptotic permanent price impact.

References

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