Selfsimilar processes with stationary increments in the second Wiener chaos

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March 31, 2011

Abstract

We study selfsimilar processes with stationary increments in the second Wiener chaos. We show that, in contrast with the first Wiener chaos which contains only one such process (the fractional Brownian motion), there is an infinity of selfsimilar processes with stationary increments living in the Wiener chaos of order 2. We prove some limit theorems which provide a mechanism to construct such processes.

2010 AMS Classification Numbers: 60F05, 60H05, 91G70.

Key words: selfsimilar processes, stationary increments, second Wiener chaos, limit theorems, multiple stochastic integrals, weak convergence.

1 Introduction

The selfsimilar processes with stationary increments have been widely studied. Let $H > 0$. A stochastic process $Y = (Y_t)_{t \geq 0}$ is $H$-selfsimilar if for any $c > 0$ the processes $(Y_{ct})_{t \geq 0}$ and $(c^H Y_t)_{t \geq 0}$ have the same finite dimensional distributions. Here $H$ is called the selfsimilar parameter of $Y$. The process $(Y_t)_{t \geq 0}$ has stationary increments if $(Y_t)_{t \geq 0}$ and $(Y_{t+h} - Y_h)_{t \geq 0}$ have the same finite dimensional distributions for every $h > 0$. Let $H \in (0, 1]$. All $H$-selfsimilar processes with stationary increments and with finite variances have the same
covariance function given by

$$R(t, s) = \frac{C}{2} \left( t^{2H} + s^{2H} - |t - s|^{2H} \right), \quad \forall s, t \geq 0,$$

where $C$ is the second moment of the process at time 1. We refer to the monographs [4] and [10] for a complete exposition on selfsimilar processes. Since the Gaussian processes are characterized by their covariance, there is only one Gaussian selfsimilar process with stationary increments (and with unit variance at time 1). This is the fractional Brownian motion. The Gaussian processes live in the first Wiener chaos, that is, they can basically be expressed as single integrals with respect to the Wiener process.

The purpose of this paper is to discuss selfsimilar processes in the second Wiener chaos. The elements of the second Wiener chaos are double iterated stochastic integrals with respect to the Wiener process. The law of such processes is not given anymore by their covariance function, therefore the fact that two selfsimilar process with stationary increments in the second Wiener chaos have the same covariance does not imply the equivalence of finite dimensional distribution of these processes. It is then expected to have more than one selfsimilar process in the second Wiener chaos. We will actually show that there exists an infinity of such processes.

This paper is organized as follows. In Section 2 we introduce the multiple Wiener-Itô integrals that will be used throughout the paper. In Section 3 we study the so-called non-symmetric Rosenblatt process, which depends on two parameters and by suitably choosing these parameters, we obtain an infinity of selfsimilar processes with stationary increments in the second Wiener chaos. The analysis of the laws of these processes are based on the cumulants and this is done in Section 4. Sections 5 and 6 contain the proof of some non-central limit theorems in which selfsimilar processes with stationary increments appear as limits. Our results extend those from [1], [3] or [11]. We finish our paper with some thoughts about how many selfsimilar processes with stationary increments are in the second Wiener chaos and how they can be obtained as limits in non-central-type limit theorems.

## 2 Multiple Wiener-Itô Integrals

Let $B = (B_t)_{t \in \mathbb{R}}$ be a classical Wiener process on a standard probability space $(\Omega, \mathcal{F}, \mathbb{P})$. If $f \in L^2(\mathbb{R}^n)$ with $n \geq 1$ integer, we introduce the multiple Wiener-Itô integral of $f$ with respect to $B$. The basic reference is the monograph [8]. Let $f \in \mathcal{S}_n$ be an elementary function with $n$ variables that can be written as $f = \sum_{t_1, \ldots, t_n} c_{t_1, \ldots, t_n} 1_{A_{t_1} \times \cdots \times A_{t_n}}$, where the coefficients satisfy $c_{i_1, \ldots, i_n} = 0$ if two indexes $i_k$ and $i_l$ are equal and the sets $A_i \in \mathcal{B}(\mathbb{R})$ are pairwise disjoint. For such a step function $f$ we define

$$I_n(f) = \sum_{t_1, \ldots, t_n} c_{t_1, \ldots, t_n} B(A_{t_1}) \ldots B(A_{t_n})$$
where we put \( B(A) = \int_\mathbb{R} 1_A(s)dB_s \). It can be seen that the application \( I_n \) constructed above from \( S_n \) to \( L^2(\Omega) \) is an isometry on \( S_n \) in the sense
\[
E[I_n(f)I_m(g)] = n!(f, g)_{L^2(\mathbb{R}^n)} \quad \text{if } m = n
\]
and
\[
E[I_n(f)I_m(g)] = 0 \quad \text{if } m \neq n.
\]
Since the set \( S_n \) is dense in \( L^2(\mathbb{R}^n) \) for every \( n \geq 1 \) the mapping \( I_n \) can be extended to an isometry from \( L^2(\mathbb{R}^n) \) to \( L^2(\Omega) \) and the above properties hold true for this extension.

It also holds that \( I_n(f) = I_n(\tilde{f}) \), where \( \tilde{f} \) denotes the symmetrization of \( f \) defined by
\[
\tilde{f}(x_1, \ldots, x_n) = \frac{1}{n!} \sum_{\sigma} f(x_{\sigma(1)}, \ldots, x_{\sigma(n)}),
\]
\( \sigma \) running over all permutations of \( \{1, ..., n\} \). We will need the general formula for calculating products of Wiener chaos integrals of any orders \( m, n \) for any symmetric integrands \( f \in L^2(\mathbb{R}^m) \) and \( g \in L^2(\mathbb{R}^n) \), which is
\[
I_m(f)I_n(g) = \sum_{\ell=0}^{m \wedge n} \ell! \binom{m}{\ell} \binom{n}{\ell} I_{m+n-2\ell}(f \otimes_\ell g),
\]
where the contraction \( f \otimes_\ell g \) is defined by
\[
(f \otimes_\ell g)(s_1, \ldots, s_{m-\ell}, t_1, \ldots, t_{n-\ell})
= \int_{T^{m+n-2\ell}} f(s_1, \ldots, s_{m-\ell}, u_1, \ldots, u_\ell)g(t_1, \ldots, t_{n-\ell}, u_1, \ldots, u_\ell)du_1 \ldots du_\ell.
\]

3 A class of selfsimilar processes with stationary increments in the second Wiener chaos

The purpose of this section is to discuss a particular class of selfsimilar processes with stationary increments living in the second Wiener chaos. This class contains an infinite number of elements and all of them have different finite dimensional distributions. We introduce our set as follows. Let \( H_1, H_2 \in (0, 1) \) such that
\[
H_1 + H_2 > 1.
\]
Consider the stochastic process \( Y^{H_1,H_2} = (Y_t^{H_1,H_2})_{t \geq 0} \) given by, for every \( t \geq 0 \),
\[
Y_t^{H_1,H_2} = c(H_1, H_2) \int_{\mathbb{R}^2} \left( \int_0^t (u - y_1)^{\frac{H_1}{2} - 1}(u - y_2)^{\frac{H_2}{2} - 1} du \right) dY_{y_1} dY_{y_2},
\]
where the integral above is a multiple Wiener-Itô stochastic integral of order 2 introduced in Section 2.

The constant \(c(H_1, H_2)\) will be chosen such that \(E[Y_t^2] = 1\). This constant plays actually an important role in our paper. It will be explicitly calculated later.

**Proposition 1** The process \(\left(Y_{t}^{H_1, H_2}\right)_{t \in [0, \infty)}\) is \(\frac{1}{2}(H_1 + H_2)\) selfsimilar and it has stationary increments.

**Proof:** Let \(c > 0\). We have

\[
Y_{ct}^{H_1, H_2} = c(H_1, H_2) \int_{\mathbb{R}^2} \left( \int_0^{ct} (u - y_1)^{\frac{H_1}{2} - 1} (u - y_2)^{\frac{H_2}{2} - 1} du \right) dB_{y_1} dB_{y_2}
\]

\[
= c(H_1, H_2) \int_{\mathbb{R}^2} \left( \int_0^t (cu - y_1)^{\frac{H_1}{2} - 1} (cu - y_2)^{\frac{H_2}{2} - 1} du \right) dB_{y_1} dB_{y_2}
\]

\[
= c(H_1, H_2) \int_{\mathbb{R}^2} \left( \int_0^t (cu - cy_1)^{\frac{H_1}{2} - 1} (cu - cy_2)^{\frac{H_2}{2} - 1} du \right) dB_{cy_1} dB_{cy_2}
\]

\[
d = c^{\frac{H_1 + H_2}{2}} Y_{t}
\]

where we have used the \(\frac{1}{2}\) selfsimilarity of the Wiener process \(B\). Here \(\equiv\) means equivalence of all finite dimensional distributions. It is obvious that the process \(\left(Y_{t}^{H_1, H_2}\right)\) has stationary increments since for every \(h > 0\) and \(t \geq 0\) we have \(\left(Y_{t+h}^{H_1, H_2} - Y_{h}^{H_1, H_2}\right) \equiv \left(Y_{t}^{H_1, H_2}\right)\).

**Remark 1** The particular case \(H_1 = H_2 = H\) corresponds to the Rosenblatt process as defined in [3], [11]. We will call this process in our paper as the symmetric Rosenblatt process. The process \(Y^{H_1, H_2}\) with \(H_1 \neq H_2\) will be called non-symmetric Rosenblatt process. Also note that the selfsimilar parameter of \(Y_{t}^{H_1, H_2}\) is always contained in the interval \((\frac{1}{2}, 1)\).

Let us denote by \(f_t\) the kernel of \(Y_{t}^{H_1, H_2}\), that is,

\[
f_t(y_1, y_2) = c(H_1, H_2) \int_0^t (u - y_1)^{\frac{H_1}{2} - 1} (u - y_2)^{\frac{H_2}{2} - 1} du
\]

(6)

for every \(y_1, y_2 \in \mathbb{R}\). The kernel \(f_t\) is in general not symmetric with respect to the variables \(y_1, y_2\) (except the case \(H_1 = H_2\)). We denote by \(\tilde{f}_t\) its symmetrization

\[
\tilde{f}_t(y_1, y_2) = \frac{1}{2}(f_t(y_1, y_2) + f_t(y_2, y_1)).
\]

We will need the following lemma throughout the paper.
Lemma 1 Let \( v < u \) and \( H_1, H_2 \in (0, 1) \). Then

\[
\int_{-\infty}^{v} (u - y_1)^{\frac{H_1}{2} - 1}(v - y_1)^{\frac{H_2}{2} - 1} dy_1 = \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2} \right) (u - v)^{\frac{H_1 + H_2}{2} - 1},
\]

where \( \beta(a, b) = \int_0^1 x^{a-1}(1 - x)^{b-1}dx \) denotes the beta function with parameters \( a, b > 0 \). Therefore, for every \( u, v > 0 \)

\[
\int_{-\infty}^{u \wedge v} (u - y_1)^{\frac{H_1}{2} - 1}(v - y_1)^{\frac{H_2}{2} - 1} dy_1 \\
= \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2} \right) (u - v)^{\frac{H_1 + H_2}{2} - 1} + \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2} \right) (u - v)^{\frac{H_1 + H_2}{2} - 1}.
\]

Proof: This follows by making the change of variables \( z = \frac{u - y_1}{u - y} \) with \( dy_1 = \frac{u - y}{(1 - z)^2} dz \) and from the fact that \((-x)_+ = x_+\).

Remark 2 Using the well-known properties of the beta and gamma functions (recall that \( \Gamma(a) = \int_0^\infty x^{a-1}e^{-x}dx \) for \( a > 0 \))

\[
\beta(a, b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)} \quad \text{and} \quad \Gamma(a)\Gamma(1-a) = \frac{\pi}{\sin(\pi a)}
\]

we can give a variant of the above lemma:

\[
\int_{-\infty}^{u \wedge v} (u - y_1)^{\frac{H_1}{2} - 1}(v - y_1)^{\frac{H_2}{2} - 1} dy_1 \\
= \Gamma \left( 1 - \frac{H_1 + H_2}{2} \right) \left( \Gamma \left( \frac{H_1}{2} \right) \Gamma \left( 1 - \frac{H_2}{2} \right) \right)^{-1} + \Gamma \left( 1 - \frac{H_1 + H_2}{2} \right) \left( \Gamma \left( \frac{H_2}{2} \right) \Gamma \left( 1 - \frac{H_1}{2} \right) \right)^{-1} |u - v|^{H-1}
\]

\[
= \Gamma \left( 1 - \frac{H_1 + H_2}{2} \right) \Gamma \left( \frac{H_1}{2} \right) \Gamma \left( \frac{H_2}{2} \right) |u - v|^{H-1} a(H_1, H_2),
\]

where \( a(H_1, H_2) = \sin(\pi H_2/2) \) if \( v < u \) and \( a(H_1, H_2) = \sin(\pi H_1/2) \) if \( u < v \). Or otherwise

\[
\int_{-\infty}^{u \wedge v} (u - y_1)^{\frac{H_1}{2} - 1}(v - y_1)^{\frac{H_2}{2} - 1} dy_1 \\
= \Gamma \left( 1 - \frac{H_1 + H_2}{2} \right) \Gamma \left( \frac{H_1}{2} \right) \Gamma \left( \frac{H_2}{2} \right) |u - v|^{H-1} (\sin(\pi H_2/2) + \sin(\pi H_2/2)).
\]

We will now compute the renormalizing constant appearing in (5).

Lemma 2 Assume \( H_1, H_2 \in (0, 1) \) and (4). The normalizing constant \( c(H_1, H_2) \) appearing in the definition of \( Y^{H_1,H_2} \) in (5) is given by

\[
c(H_1, H_2) = \frac{1}{2H(H-1)} \left( \beta \left( 1 - H_1, \frac{H_1}{2} \right) \beta \left( 1 - H_2, \frac{H_2}{2} \right) + \beta \left( 1 - H, \frac{H_1}{2} \right) \beta \left( H, \frac{H_2}{2} \right) \right).
\]
Proof: Since $Y_t^{H_1, H_2} = I_2(f_t) = I_2(\tilde{f}_t)$ for every $t \geq 0$ with $f_t$ given by (6), we have from the isometry property of multiple stochastic integrals (1)

$$E \left[ (Y_t^{H_1, H_2})^2 \right]$$

$$= 2\|\tilde{f}_t\|^2_{L^2(\mathbb{R}^2)} = 2 \int_{\mathbb{R}^2} \tilde{f}_t^2(y_1, y_2)dy_1dy_2$$

$$= \frac{1}{2} c(H_1, H_2)^2 \int_{\mathbb{R}^2} \left( \int_0^t (u - y_1)^{H_1+1} (u - y_2)^{H_2+1} du + \int_0^t (u - y_2)^{H_1+1} (u - y_1)^{H_2+1} du \right) \times \left( \int_0^t (v - y_1)^{H_1+1} (v - y_2)^{H_2+1} dv + \int_0^t (v - y_2)^{H_1+1} (v - y_1)^{H_2+1} dv \right) dy_1dy_2$$

$$= \frac{1}{2} c(H_1, H_2)^2 \int_{\mathbb{R}^2} \left[ \left( \int_0^t (u - y_1)^{H_1+1} (u - y_2)^{H_2+1} du \int_0^t (v - y_1)^{H_1+1} (v - y_2)^{H_2+1} dv \right) + \left( \int_0^t (u - y_1)^{H_1+1} (u - y_2)^{H_2+1} du \int_0^t (v - y_1)^{H_1+1} (v - y_2)^{H_2+1} dv \right) + \left( \int_0^t (u - y_2)^{H_2+1} (u - y_1)^{H_1+1} du \int_0^t (v - y_1)^{H_1+1} (v - y_2)^{H_2+1} dv \right) + \left( \int_0^t (u - y_2)^{H_2+1} (u - y_1)^{H_1+1} du \int_0^t (v - y_1)^{H_1+1} (v - y_2)^{H_2+1} dv \right) \right] dy_1dy_2$$

and by interchanging the order of integration and noticing that the first and third summands, and the second and fourth, coincide

$$c(H_1, H_2)^{-2} E \left[ (Y_t^{H_1, H_2})^2 \right]$$

$$= \int_0^t \int_0^t \left[ \left( \int_{-\infty}^{u/v} dy_1 (u - y_1)^{H_1+1} (v - y_1)^{H_1+1} \right) \left( \int_{-\infty}^{u/v} dy_2 (u - y_2)^{H_2+1} (v - y_2)^{H_2+1} \right) + \left( \int_{-\infty}^{u/v} dy_1 (u - y_1)^{H_1+1} (v - y_1)^{H_1+1} \right) \left( \int_{-\infty}^{u/v} dy_2 (u - y_2)^{H_2+1} (v - y_2)^{H_2+1} \right) \right] dv.\!$$

Observe that the function inside the integral $dudv$ is symmetric with respect to the variables $u, v$. Therefore

$$c(H_1, H_2)^{-2} E \left[ (Y_t^{H_1, H_2})^2 \right]$$

$$= 2 \int_0^t du \int_0^u \left[ \left( \int_{-\infty}^{v} dy_1 (u - y_1)^{H_1+1} (v - y_1)^{H_1+1} \right) \left( \int_{-\infty}^{v} dy_2 (u - y_2)^{H_2+1} (v - y_2)^{H_2+1} \right) + \left( \int_{-\infty}^{v} dy_1 (u - y_1)^{H_1+1} (v - y_1)^{H_1+1} \right) \left( \int_{-\infty}^{v} dy_2 (u - y_2)^{H_2+1} (v - y_2)^{H_2+1} \right) \right] dv.\!$$
We obtain, using Lemma 1,
\[
c(H_1, H_2)^{-2} \mathbb{E}\left[\left(Y_{t}^{H_1, H_2}\right)^2\right]
= 2 \left(\beta\left(1 - H_1, \frac{H_1}{2}\right) \beta\left(1 - H_2, \frac{H_2}{2}\right) + \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2}\right) \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2}\right)\right)
\times \int_0^t du \int_0^u (u - v)^H_1 + H_2 - 2 dv
= \left(\beta\left(1 - H_1, \frac{H_1}{2}\right) \beta\left(1 - H_2, \frac{H_2}{2}\right) + \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2}\right) \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2}\right)\right)
\times \frac{1}{(H_1 + H_2)(2(H_1 + H_2) - 1)} t^{2H}.
\]
If \(H_1 + H_2 = 2H\), then
\[
c(H_1, H_2)^{-2} \mathbb{E}\left[\left(Y_{t}^{H_1, H_2}\right)^2\right]
= \left(\beta\left(1 - H_1, \frac{H_1}{2}\right) \beta\left(1 - H_2, \frac{H_2}{2}\right) + \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2}\right) \beta\left(1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2}\right)\right) \frac{1}{H(2H - 1)} t^{2H},
\]
which implies
\[
c(H_1, H_2)^{-2}
= \frac{1}{H(2H - 1)} \left(\beta\left(1 - H_1, \frac{H_1}{2}\right) \beta\left(1 - H_2, \frac{H_2}{2}\right) + \beta\left(1 - H, \frac{H_1}{2}\right) \beta\left(1 - H, \frac{H_2}{2}\right)\right). \quad (7)
\]

**Remark 3** In the particular case \(H_1 = H_2 = H\) we have
\[
c(H, H) := c(H) = \frac{2}{H(2H - 1)} \beta\left(1 - H, \frac{H}{2}\right)^2
\]
and it coincides with the constant used in e.g. [12].

**Remark 4** Using again \(\beta(a, b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a + b)}\), the renormalizing constant \(C(H_1, H_2)\) can be expressed in terms of gamma functions as follows
\[
c(H_1, H_2)^{-2} = \frac{1}{H(2H - 1)} \left[\frac{\Gamma(1 - H_1)\Gamma(H_1/2)\Gamma(1 - H_2)\Gamma(H_2/2)}{\Gamma(1 - H_1)\Gamma(1 - H_2)} + \frac{\Gamma(1 - H)\Gamma(H_1/2)\Gamma(1 - H)\Gamma(H_2/2)}{\Gamma(1 - H_1)\Gamma(1 - H_2)}\right]
= \frac{\Gamma(H_1/2)\Gamma(H_2/2)}{H(2H - 1)\Gamma(1 - H_1)\Gamma(H_1/2)\Gamma(1 - H_2)\Gamma(1 - H_2)} \left[\Gamma(1 - H_1)\Gamma(1 - H_2) + \Gamma(1 - H)^2\right].
\]
4 Cumulants of the non-symmetric Rosenblatt process

We will prove in the section that the processes $Y^{H_1,H_2}$ given by (5) have different laws upon the values of the self-similar parameters $H_1$ and $H_2$. We will use the concept of cumulant. The cumulants of a random variable $X$ having all moments appear as the coefficients in the Maclaurin series of $g(t) = \log Ee^{tX}$, $t \in \mathbb{R}$. The first cumulant $c_1$ is the expectation of $X$ while the second one is the variance of $X$. Generally, the $n$th cumulant is given by $g^{(n)}(0)$. The key fact is that for random variables in the second Wiener chaos the cumulants characterizes the law.

Let us consider a multiple integral $I_2(f)$ with $f \in L^2(\mathbb{R}^2)$ symmetric. Then the $m$th cumulant of the random variable $I_2(f)$ are given by (see [7] or [5])

$$c_m(I_2(f)) = 2^{m-1}(m-1)! \int_{\mathbb{R}^m} f(y_1, y_2)f(y_2, y_3)\ldots f(y_{m-1}, y_m)f(y_m, y_1)dy_1\ldots dy_m \quad (8)$$

**Remark 5** It is known that the law of a multiple integral of order two is completely determined by its cumulants in the sense that, if two multiple integrals of order 2 have the same cumulants, then their distributions are the same. For this result we refer to [5].

Let us compute the cumulants of the random variable $I_2(\bar{f}_t)$ with fixed $t \geq 0$ and $f_t$ given by (6). Using formula (8) and the expression of the kernel $\bar{f}$, we get

$$c_m(I_2(\bar{f}_t)) = 2^{m-1}(m-1)!2^{-m}c(H_1, H_2)^m$$

$$\int_{\mathbb{R}^m} \left( \int_0^t (u_1 - y_1)^{H_1-1}(u_1 - y_2)^{H_2-1}du_1 + \int_0^t (u_1 - y_2)^{H_1-1}(u_1 - y_1)^{H_2-1}du_1 \right)$$

$$\times \left( \int_0^t (u_2 - y_2)^{H_1-1}(u_2 - y_3)^{H_2-1}du_2 + \int_0^t (u_2 - y_3)^{H_1-1}(u_2 - y_2)^{H_2-1}du_2 \right)$$

$$\ldots$$

$$\times \left( \int_0^t (u_{m-1} - y_{m-1})^{H_1-1}(u_{m-1} - y_m)^{H_2-1}du_{m-1} + \int_0^t (u_{m-1} - y_m)^{H_1-1}(u_{m-1} - y_{m-1})^{H_2-1}du_{m-1} \right)$$

$$\times \left( \int_0^t (u_m - y_m)^{H_1-1}(u_m - y_1)^{H_2-1}du_m + \int_0^t (u_m - y_1)^{H_1-1}(u_m - y_m)^{H_2-1}du_m \right)$$

$$dy_1\ldots dy_m.$$

We can state the main result of this section.

**Proposition 2** Let us consider the process $(Y_t^{H_1,H_2})_{t \geq 0}$ given by (5). For any couples $(H_1, H_2), (H'_1, H'_2) \in (0,1)^2$ with $H_1 + H_2 = H'_1 + H'_2 = 2H$ such that $(H_1, H_2) \neq (H'_1, H'_2)$ and for any $t > 0$, the laws of the random variables $Y_t^{H_1,H_2}$ and $Y_t^{H'_1,H'_2}$ are different.
**Proof:** It suffices to show that for fixed $t$ the two random variables $Y_t^{H_1, H_2}$ and $Y_t^{H_1, H_2'}$ have at least one different cumulant. The first two cumulants (that is, the expectation and the variance) of these two random variables are the same since $Y_t^{H_1, H_2}$ is an $H$-selfsimilar process with stationary increments. Let us compute the third cumulant.

Let us consider the case $m = 3$. Then, by changing the order of integration, we get

$$c_3(I_2(f_t)) = c(H_1, H_2)^3 \int_0^t \int_0^t \int_0^t \left[ \left( \int_{\mathbb{R}} (u_1 - y)^{\frac{H_1}{2} - 1} (u_3 - y)^{\frac{H_2}{2} - 1} \, dy \right) \left( \int_{\mathbb{R}} (u_1 - y)^{\frac{H_3}{2} - 1} (u_2 - y)^{\frac{H_3}{2} - 1} \, dy \right) \right. \times \left( \int_{\mathbb{R}} (u_2 - y)^{\frac{H_3}{2} - 1} (u_3 - y)^{\frac{H_3}{2} - 1} \, dy \right) \left. \right] \, du_1 \, du_2 \, du_3.$$
\[\begin{align*}
&= c(H_1, H_2)^3 \int_0^t \int_0^t \int_0^t [g_{H_1, H_2}(u_1, u_2, u_3) + g_{H_1, H_2}(u_3, u_2, u_1) + f_{H_1, H_2}(u_1, u_2, u_3) \\
&\quad + f_{H_1, H_2}(u_1, u_3, u_2) + f_{H_1, H_2}(u_2, u_1, u_3) + f_{H_1, H_2}(u_2, u_3, u_1) \\
&\quad + f_{H_1, H_2}(u_3, u_1, u_2) + f_{H_1, H_2}(u_3, u_2, u_1)] \, du_1 du_2 du_3,
\end{align*}\]

where we have denoted by
\[\begin{align*}
g_{H_1, H_2}(u_1, u_2, u_3) &= \left( \int \frac{H_1}{y} - 1 (u_1 - y) \frac{\frac{H_2}{y}}{2} - 1 dy \right) \\
&\times \left( \int \frac{H_2}{y} - 1 (u_2 - y) \frac{u_3}{2} - 1 dy \right) \\
&\times \left( \int \frac{H_1}{y} - 1 (u_3 - y) \frac{H_2}{2} - 1 dy \right),
\end{align*}\]

and
\[\begin{align*}
f_{H_1, H_2}(u_1, u_2, u_3) &= \left( \int \frac{H_1}{y} - 1 (u_1 - y) \frac{\frac{H_2}{y}}{2} - 1 dy \right) \\
&\times \left( \int \frac{H_2}{y} - 1 (u_2 - y) \frac{u_3}{2} - 1 dy \right) \\
&\times \left( \int \frac{H_1}{y} - 1 (u_3 - y) \frac{H_2}{2} - 1 dy \right).
\end{align*}\]

Therefore, the function under the integral \( du_1 du_2 du_3 \) is symmetric with respect to the variables \( u_1, u_2, u_3 \). The integral \( \int_0^t \int_0^t \int_0^t du_1 du_2 du_3 \) is then equal to
\[3! \int_{u_3 < u_2 < u_1, u_2, u_3 \in [0, t]} du_1 du_2 du_3.\]

Also, from Lemma 2 it holds that, for \( u_3 < u_1 < u_2 \)
\[\begin{align*}
g_{H_1, H_2}(u_1, u_2, u_3) &= \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2} \right) (u_1 - u_3) \frac{H_1 + H_2}{2} - 1 \\
&\times \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2} \right) (u_1 - u_2) \frac{H_1 + H_2}{2} - 1 \\
&\times \beta \left( 1 - \frac{H_1 + H_2}{2}, \frac{H_1}{2} \right) (u_2 - u_3) \frac{H_1 + H_2}{2} - 1
\end{align*}\]

and
\[\begin{align*}
f_{H_1, H_2}(u_1, u_2, u_3) &= \beta \left( 1 - H_1, \frac{H_1}{2} \right) (u_1 - u_3) \frac{H_1 + H_2}{2} - 1 \\
&\times \beta \left( 1 - H_2, \frac{H_1}{2} \right) (u_1 - u_2) \frac{H_1 + H_2}{2} - 1.
\end{align*}\]
Thus we have

\[ c_3(I_2(\tilde{f}_1)) = 3!c(H_1, H_2)^3 \]

\[ \times \beta \left(1 - \frac{H_1 + H_2}{2}, \frac{H_2}{2}\right) (u_2 - u_3)^{\frac{H_1 + H_2}{2} - 1}. \]

and using gamma integrals we get

\[ c_3(I_2(\tilde{f}_1)) = 3!c(H_1, H_2)^3 \]

\[ \frac{\Gamma(1 - H_1)\Gamma(\frac{H_1}{2})\Gamma(\frac{H_2}{2})}{(\Gamma(1 - \frac{H_1}{2})\Gamma(1 - \frac{H_2}{2}))^2} \left( \Gamma(\frac{H_1}{2})\Gamma(1 - \frac{H_1}{2}) + \Gamma(\frac{H_2}{2})\Gamma(1 - \frac{H_2}{2}) \right) \]

\[ (2\Gamma(1 - H_1)\Gamma(1 - H_2) + \Gamma(1 - H)^2) \]

\[ \int_{u_3<u_2<u_1,u_1,u_2,u_3\in[0,t]} (u_1 - u_3)^{H-1}(u_1 - u_2)^{H-1}(u_2 - u_3)^{H-1}du_1du_2du_3. \]

It is obvious, given the expression of the normalizing constant \( c(H_1, H_2) \), that if \( (H_1, H_2) \neq (H'_1, H'_2) \) then \( c_3(I_2(f_{H_1,H_2})) \neq c_3(I_2(f_{H'_1,H'_2})) \) (see also the following remark).
Remark 6 Since the gamma function can be numerically calculated for any value of the parameter (see for example http://www.efunda.com/math/gamma/findgamma.cfm), the constant appearing in the expression of the third cumulant above can be also numerically computed and it can be seen that it has different values when \((H_1, H_2) \neq (H'_1, H'_2)\) and \(H_1 + H_2 = H'_1 + H'_2\).

Example 1 There are other classes of selfsimilar process with stationary increments. For example we refer to [9] and [6]. Consider \(\alpha, \beta\) such that \(\frac{1}{2} < \alpha < \frac{3}{4}\) and \(0 < 2 - 2\alpha - \beta < 1\). Define for every \(t \geq 0\)

\[
X_t = \int_R \int_R \left( \int_0^\infty (u - y_1)^{-\alpha}(u - y_2)^{-\alpha} \left( |u|^{-\beta} - |u - t|^{-\beta} \right) \, du \right) \, dB_{y_1} \, dB_{y_2}.
\]

The process \(X = (X_t)_{t \geq 0}\) defined above is \(H\)-selfsimilar with stationary increments where \(H = 2 - \beta - 2\alpha\). The proof is immediate and follows the lines of Proposition 1. It can also be proved that for suitable choices of \(\alpha, \beta\), the law of the process \(X\) defined above is different from the law of the process \(Y\) (5). We will come back to this process \(X\) defined above in the last section.

5 Limit theorem for non-symmetric Rosenblatt process

Let \(B^{H_1}, B^{H_2}\) be two fractional Brownian motion with Hurst parameters \(H_1, H_2\) respectively. We will assume that the selfsimilar parameters \(H_1\) and \(H_2\) are both bigger than \(\frac{1}{2}\). We will also assume that the two fractional Brownian motions can be expressed as Wiener integrals with respect to the same Wiener process \(B\). This implies that \(B^{H_1}\) and \(B^{H_2}\) are not independent. We have

\[
B^{H_1}_t = c(H_1) \int_R dB_y \int_0^t (u - y)^{H_1 - 3/2} \, du, \quad B^{H_2}_t = c(H_2) \int_R dB_y \int_0^t (u - y)^{H_2 - 3/2} \, du \quad (9)
\]

where the constants \(c(H_1), c(H_2)\) are such that \(E \left[ (B^{H_1}_1)^2 \right] = E \left[ (B^{H_2}_1)^2 \right] = 1\). Actually, by applying Lemma 1 with \(H_1, H_2\) replaced by \(2H_1 - 1, 2H_2 - 1\) respectively, we get

\[
c(H_1)^2 = \frac{H_1(2H_1 - 1)}{2 - 2H_1, H_1 - \frac{1}{2}}. \quad (10)
\]

Define, for every \(N \geq 2, t \geq 0\) the sequence

\[
V_N(t) = \sum_{i=0}^{[Nt]-1} \left[ \frac{E \left[ B^{H_1}_{\frac{H_1}{N}} - B^{H_1}_{\frac{H_1}{N}} \right] \left( B^{H_2}_{\frac{H_2}{N}} - B^{H_2}_{\frac{H_2}{N}} \right)}{E \left[ B^{H_1}_{\frac{H_1}{N}} - B^{H_1}_{\frac{H_1}{N}} \right] \left( B^{H_2}_{\frac{H_2}{N}} - B^{H_2}_{\frac{H_2}{N}} \right) - 1} \right]. \quad (11)
\]

It is well-known that, in the case \(H_1 = H_2 = H \in \left( \frac{3}{4}, 1 \right)\), the (renormalized) sequence \((V_N(t))_{t \geq 0}\) converges, as \(N \to \infty\), in the sense of finite dimensional distribution,
to a symmetric Rosenblatt process with self-similar parameter $2H - 1$. Our aim is to extend this result to the situation when $H_1 \neq H_2$. We will actually prove that, after suitable normalization, the sequence (11) converges in the sense of finite dimensional distributions to the process $Y_{H_1,H_2}$ in (5).

First, we need to understand the correlations structure of the fractional Brownian motions $B^{H_1}$ and $B^{H_2}$.

**Lemma 3** Let $t > s$. Then

$$E \left[ \left( B_t^{H_1} - B_s^{H_1} \right) \left( B_t^{H_2} - B_s^{H_2} \right) \right] = b(H_1, H_2)|t - s|^{2H}$$

where

$$b(H_1, H_2) = \frac{c(H_1)c(H_2)}{2H(2H - 1)} \left( \beta \left( 2 - 2H, H_1 - \frac{1}{2} \right) + \beta \left( 2 - 2H, H_2 - \frac{1}{2} \right) \right)$$

where $c(H_1), c(H_2)$ are given by (10).

**Proof:** Since

$$B_t^{H_1} - B_s^{H_1} = c(H_1) \int_\mathbb{R} dB_y \int_s^t (u - y)_+^{H_1 - \frac{3}{2}} du$$

we obtain, using the isometry of Wiener integrals and Lemma 1,

$$E \left[ \left( B_t^{H_1} - B_s^{H_1} \right) \left( B_t^{H_2} - B_s^{H_2} \right) \right] = c(H_1)c(H_2) \int_s^t \int_s^t du dv \int_{-\infty}^u (u - y)_+^{H_1 - \frac{3}{2}} (v - y)_+^{H_2 - \frac{3}{2}} dy$$

$$= c(H_1)c(H_2) \int_s^t du \int_s^u \beta(2 - 2H, 2H_1 - 1)(u - v)^{2H - 2} dv$$

$$+ c(H_1)c(H_2) \int_s^t dv \int_s^v \beta(2 - 2H, 2H_2 - 1)(v - u)^{2H - 2} du$$

$$= \frac{c(H_1)c(H_2)}{2H(2H - 1)} \left( \beta \left( 2 - 2H, H_1 - \frac{1}{2} \right) + \beta \left( 2 - 2H, H_2 - \frac{1}{2} \right) \right) (t - s)^{2H}.$$


**Remark 7** The above constant $b(H_1, H_2)$ is equal to 1 if $H_1 = H_2 = H$.

The following result constitutes an extension to the non-symmetric case of the non-central limit theorem proved in [1], [3], [11].

**Theorem 1** Let $V_N$ be given by (11) and assume that $H_1 + H_2 = 2H > 3$. Then, when $N \to \infty$, $c(H_1, H_2)(c(H_1)c(H_2))^{-1}b(H_1, H_2)N^{1-2H}V_N(1)$ converges in $L^2(\Omega)$ to the random variable $Y_1^{2H_1 - 1, 2H_2 - 1}$ given by (5).
Proof of Theorem 1: Using the product formula for multiple integrals (2), we can express $V_N$ as

\[ V_N(1) = N^{2H} b(H_1, H_2)^{-1} c(H_1)c(H_2) \sum_{i=0}^{N-1} \int_{\mathbb{R}} \int_{\mathbb{R}} dB_{y_1} dB_{y_2} \int_{\frac{i}{N}}^{\frac{i+1}{N}} \int_{\frac{i}{N}}^{\frac{i+1}{N}} (u - y_1)^{H_1 - \frac{3}{2}} (v - y_2)^{H_2 - \frac{3}{2}} dudv. \]

It suffices to show that the sequence

\[ N \sum_{i=0}^{N-1} \int_{\mathbb{R}} \int_{\mathbb{R}} dB_{y_1} dB_{y_2} \int_{\frac{i}{N}}^{\frac{i+1}{N}} \int_{\frac{i}{N}}^{\frac{i+1}{N}} (u - y_1)^{H_1 - \frac{3}{2}} (v - y_2)^{H_2 - \frac{3}{2}} dudv \]

converges in $L^2(\Omega)$, as $N \to \infty$, to

\[ \int_{\mathbb{R}} \int_{\mathbb{R}} dB_{y_1} dB_{y_2} \int_{0}^{1} (u - y_1)^{H_1 - \frac{3}{2}} (u - y_2)^{H_2 - \frac{3}{2}} du \]

or equivalently, by the isometry formula (1), that the sequence

\[ a_N(y_1, y_2) = N \sum_{i=0}^{N-1} \int_{\frac{i}{N}}^{\frac{i+1}{N}} \int_{\frac{i}{N}}^{\frac{i+1}{N}} (u - y_1)^{H_1 - \frac{3}{2}} (v - y_2)^{H_2 - \frac{3}{2}} dudv \]

converges in $L^2(\mathbb{R}^2)$ as $N \to \infty$ to the function

\[ a(y_1, y_2) = \int_{0}^{1} (u - y_1)^{H_1 - \frac{3}{2}} (u - y_2)^{H_2 - \frac{3}{2}} du \]

which represents the kernel of the non-symmetric Rosenblatt process. Let us estimate the $L^2(\mathbb{R}^2)$ norm of the difference $a_N - a$. We have

\[ \|a_N - a\|_{L^2(\mathbb{R}^2)} \leq \|a_N\|_{L^2(\mathbb{R}^2)} - 2 \langle a_N, a \rangle_{L^2(\mathbb{R}^2)} + \|a\|_{L^2(\mathbb{R}^2)}^2. \]

We compute separately the three quantities above. First,

\[ \|a_N\|_{L^2(\mathbb{R}^2)}^2 = N^2 \sum_{i,j=0}^{N-1} \int_{\mathbb{R}} \int_{\mathbb{R}} \left( \int_{\frac{i}{N}}^{\frac{i+1}{N}} \int_{\frac{j}{N}}^{\frac{j+1}{N}} (u - y_1)^{H_1 - \frac{3}{2}} (v - y_2)^{H_2 - \frac{3}{2}} dudv \right) dy_1 dy_2 \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]

\[ = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]}
\[ N^2 \sum_{i,j=0}^{N-1} \int_0^{i+1/2} \int_0^{j+1/2} dudv \int_0^{i+1/2} \int_0^{j+1/2} dv' \ |u-u'|^{2H_1-2}|v-v'|^{2H_2-2}du'dv', \]

where we have used Fubini theorem and Lemma 1. In the same way

\[ \langle a_N, a \rangle_{L^2(\mathbb{R}^2)} = \beta(2 - 2H_1, H_1 - \frac{1}{2}) \beta(2 - 2H_2, H_2 - \frac{1}{2}) \]
\[ N \sum_{i,j=0}^{N-1} \int_0^{i+1/2} \int_0^{j+1/2} dudv \int_0^{i+1/2} \int_0^{j+1/2} dv' \ |u-u'|^{2H_1-2}|v-v'|^{2H_2-2}du'dv' \]

and

\[ \|a\|_{L^2(\mathbb{R}^2)} = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \int_0^1 \int_0^1 |u-v|^{4H-4}dudv. \]

To summarize, we get

\[ \|a_N - a\|_{L^2(\mathbb{R}^2)}^2 = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) \]
\[ \sum_{i,j=0}^{N-1} \left[ N^2 \sum_{i,j=0}^{N-1} \int_0^{i+1/2} \int_0^{j+1/2} dudv \int_0^{i+1/2} \int_0^{j+1/2} dv' \ |u-u'|^{2H_1-2}|v-v'|^{2H_2-2}du'dv' \right. \]
\[ -2N \sum_{i=0}^{N-1} \int_0^{i+1/2} \int_0^{i+1/2} dudv \int_0^{i+1/2} \int_0^{i+1/2} dv' \ |u-u'|^{2H_1-2}|v-v'|^{2H_2-2}du'dv' \]
\[ \left. + \int_0^{i+1/2} du \int_0^{i+1/2} dudv |u-v|^{4H-4} \right] \]

and using the change of variables \( \tilde{u} = (u - \frac{i}{N}) N \) (and similarly for the other variables \( u', v, v' \)) we get

\[ \|a_N - a\|_{L^2(\mathbb{R}^2)}^2 = \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) N^{2-4H} \]
\[ \sum_{i,j=0}^{N-1} \left[ \int_0^1 \int_0^1 |u-u'| + i-j|^{2H_1-2}dudu' \int_0^1 \int_0^1 |v-v'| + i-j|^{2H_2-2}dvdv' \right. \]
\[ -2 \int_0^1 \int_0^1 |u-u'| + i-j|^{2H_1-2}|v-v'| + i-j|^{2H_2-2}dvdudv' \]
\[ \left. + \int_0^1 \int_0^1 |u-v| + i-j|^{4H-4}dudv \right] \]
\[
\leq \beta \left( 2 - 2H_1, H_1 - \frac{1}{2} \right) \beta \left( 2 - 2H_2, H_2 - \frac{1}{2} \right) N^{3-4H}
\]
\[
\sum_{k \in \mathbb{Z}} \left[ \int_0^1 \int_0^1 |u - u' + k|^{2H_1 - 2} du du' \int_0^1 \int_0^1 |v - v' + k|^{2H_2 - 2} dv dv' \right. \\
- 2 \int_0^1 \int_0^1 \left( u - u' + k \right)^{2H_1 - 2} |v - u' + k|^{2H_2 - 2} du dv' + \int_0^1 \int_0^1 |u - v + k|^{4H - 4} du dv']
\]

As in [2], proof of Proposition 3.1. we can prove that the sum over \( k \in \mathbb{Z} \) is finite. Indeed, this sum can be written as
\[
\sum_{k \in \mathbb{Z}} k^{4H - 4} F \left( \frac{1}{k} \right)
\]
where
\[
F(x) = \left[ \int_0^1 \int_0^1 |(u - u)x + 1|^{2H_1 - 2} du du' \int_0^1 \int_0^1 |(v - v)x + 1|^{2H_2 - 2} dv dv' \right. \\
- 2 \int_0^1 \int_0^1 |(u - u')x + 1|^{2H_1 - 2} |(v - u')x + 1|^{2H_2 - 2} du dv' + \int_0^1 \int_0^1 |(u - v)x + 1|^{4H - 4} du dv'.
\]

The conclusion follows since \( \frac{3}{4} < H < 1 \) behaves as \( x \) for \( x \) close to zero.

\[\text{Remark 8} \quad \text{The condition } H_1 + H_2 > \frac{3}{2} \text{ is natural since it extends the classical condition } H > \frac{3}{4} \text{ necessary to obtain non-Gaussian limit if } V_N \text{ in the symmetric case.}\]

By following exactly the lines of the above proof, the following corollary is immediate.

**Corollary 1** Let \( V_N \) be as in (11) and assume \( 2H = H_1 + H_2 > \frac{3}{4} \). The sequence of stochastic processes
\[
\left( c(H_1, H_2) (c(H_1) c(H_2))^{-1} b(H_1, H_2) N^{1-2H} V_N(t) \right)_{t \geq 0}
\]
converges in the sense of finite dimensional distributions as \( N \to \infty \) to the stochastic process \( (Y_t^{H_1, H_2})_{t \geq 0} \).

**Corollary 2** Consider \( B^{H_1}, B^{H_2} \) as before and assume \( 2H = H_1 + H_2 > \frac{3}{4} \). Set, for every \( t \geq 0 \),
\[
S_N(t) = \sum_{i=0}^{[Nt]-1} \left( B_{i+1}^{H_1} - B_i^{H_1} \right) \left( B_{i+1}^{H_2} - B_i^{H_2} \right) - \mathbb{E} \left[ \left( B_{i+1}^{H_1} - B_i^{H_1} \right) \left( B_{i+1}^{H_2} - B_i^{H_2} \right) \right]
\]
Then the sequence of stochastic processes

\[(c(H_1, H_2)(c(H_1)c(H_2))^{-1} N^{1-2H} S_N(t))_{t \geq 0}\]

converges as \(N \to \infty\) to \((Y^{H_1,H_2}_t)_{t \geq 0}\) in the sense of finite dimensional distributions.

**Proof:** Since for every \(t \geq 0\) we have \(S_N(t) = I_2(g_t)\) with

\[g_t(y_1, y_2) = \int_i^{i+1} \int_i^{i+1} (u - y_1)_+^{H_1-\frac{3}{2}} (u - y_2)_+^{H_2-\frac{3}{2}} du dv, \quad y_1, y_2 \in \mathbb{R}\]

by using the change of variable as in the proof of Proposition 1, it can be seen that \(V_N\) has the same law as \(b(H_1, H_2)^{-1} S_N\). \(\square\)

**6 Generalization and thoughts: how many selfsimilar processes with stationary increments are in the second Wiener chaos?**

It is well-known that in the case \(H_1 = H_2 = H\) the result in Corollary 2 is still true if \(H_2 \left( B_{i+1}^{H_1} - B_i^{H_1} \right) \) \((H_2 \text{ is the Hermite polynomial with degree 2, see below the definition})\) is replaced by \(h \left( B_{i+1}^{H_1} - B_i^{H_1} \right)\) where \(h\) is function with Hermite rank equal to 2. We propose here a more general version of Corollary 2 in the non-symmetric case. Let us define, for every \(t \geq 0\)

\[W_N(t) = N^{1-2H} \sum_{i=0}^{[Nt]-1} \left[ \left( B_{i+1}^{H_1} - B_i^{H_1} \right) g \left( B_{i+1}^{H_2} - B_i^{H_2} \right) - c_0 \right] \quad (12)\]

where \(c_0 = \mathbb{E} \left[ \left( B_{i+1}^{H_1} - B_i^{H_1} \right) g \left( B_{i+1}^{H_2} - B_i^{H_2} \right) \right]\) and where \(g\) is a deterministic function with Hermite rank equal to one which has a finite expansion into Hermite polynomials of the form

\[g(x) = \sum_{q=1}^{M} c_q H_q(x) \quad (13)\]

where \(M \geq 1\) and \(H_n\) denotes the \(n\)th Hermite polynomial

\[H_n(x) = \frac{(-1)^n}{n!} \exp \left( \frac{x^2}{2} \right) \frac{d^n}{dx^n} \left( \exp \left( -\frac{x^2}{2} \right) \right), \quad x \in \mathbb{R}.\]
Theorem 2 Consider two fractional Brownian motions \(B^{H_1}\) and \(B^{H_2}\) given by (9) with \(H_1 + H_2 = 2H > \frac{3}{2}\). Let \(g : \mathbb{R} \rightarrow \mathbb{R}\) be a deterministic function given by (13) such that for every \(q \geq 2\)

\[(2H_2 - 2)(q - 1) < -1.\]  

Then the sequence of stochastic processes \((W_N(t))_{t \geq 0}\) converges in the sense of finite dimensional distributions as \(N \rightarrow \infty\) to the process \(c_1 c(H_1, H_2) c(H_1) c(H_2) b(H_1, H_2)^{-1} Y^{H_1, H_2}\) in (5).

Remark 9 Assumption (14) excludes the existence of terms with \(q = 2\) in the expansion of \(g\).

Proof: Again we assume \(t = 1\). We have, since \(H_q(I_1(\varphi)) = \frac{1}{q!} I_q(\varphi)\) (see, e.g. [8]),

\[
W_N(1) = N^{1-2H} \sum_{i=0}^{N-1} \left( B_{i+1}^{H_1} - B_i^{H_1} \right) \sum_{q=1}^{M} c_q \frac{1}{q!} I_q(f_{q,i,H_2}) - c_0
\]

where

\[
f_{q,i,H_2}(y_1, \ldots, y_q) = \int_{[i,i+1]^q} (u_1 - y_1)^{H_2 - \frac{3}{2}} \ldots (u_q - y_q)^{H_2 - \frac{3}{2}} du_1 \ldots du_q.
\]

Thus

\[
W_N(1) = N^{1-2H} \sum_{i=0}^{N-1} I_1(f_{1,i,H_1}) \sum_{q=1}^{M} c_q \frac{1}{q!} I_q(f_{q,i,H_2})
\]

\[
= N^{1-2H} c_1 \sum_{i=0}^{N-1} I_1(f_{1,i,H_1}) I_1(f_{1,i,H_2}) + N^{1-2H} \sum_{q=2}^{M} \sum_{i=0}^{N-1} I_1(f_{1,i,H_1}) c_q \frac{1}{q!} I_q(f_{q,i,H_2}).
\]

From Theorem 1 it holds that the first summand above converges in to the desired limit. Let us show that the remaining term

\[
R_N := N^{1-2H} \sum_{i=0}^{N-1} I_1(f_{1,i,H_1}) I_q(f_{q,i,H_2})
\]

converges to zero in \(L^2(\Omega)\) for every \(q \geq 2\). By the product formula for multiple integrals (2), we can write

\[
R_N = N^{1-2H} \sum_{i=0}^{N-1} I_{q+1}(f_{1,i,H_1} \otimes f_{q,i,H_2}) + q N^{1-2H} \sum_{i=0}^{N-1} I_{q-1}(f_{1,i,H_1} \otimes f_{q,i,H_2})
\]

\[
= N^{1-2H} \sum_{i=0}^{N-1} [I_{q+1}(f_{1,i,H_1} \otimes f_{q,i,H_2}) + c(H_1, H_2, q) I_{q-1}(f_{q-1,i,H_2})]
\]
\[ R_{N,1} + R_{N,2} \]

(here \( c(H_1, H_2, q) \) denotes a generic constant depending on \( H_1, H_2, q \) that may change from line to line) where we used the fact that, by Lemma 1,

\[
\begin{align*}
(j_{1,i,H_1} \otimes 1 f_{q,i,H_2})(y_1, \ldots y_{q-1}) &= \left( \int_{\mathbb{R}} dx f_{1,i,H_1}(x) f_{1,i,H_2}(x) \right) I_{q-1}(f_{q-1,i,H_2}) \\
&= c(H_1, H_2, q) \int_i^{i+1} \int_j^{j+1} |u - v|^{H_1 + H_2 - 2} dudv = c(H_1, H_2, q).
\end{align*}
\]

We first treat the term \( R_{N,1} \). More precisely we show that this term converges to zero in \( L^2(\Omega) \) as \( N \to \infty \). We have, since for any square integrable function \( \|\tilde{f}\| \leq \|f\| \) (below \( a_N \sim b_N \) means that the sequences \( a_N \) and \( b_N \) have the same limit as \( N \to \infty \))

\[
\mathbb{E} \left[ |R_{N,1}|^2 \right] \leq c(H_1, H_2, q) N^{2-4H} \sum_{i,j=0}^{N-1} \left( \int_i^{i+1} \int_j^{j+1} |u - v|^{2H_1 - 2} dudv \right) \sum_{i,j=0; i \neq j}^{N-1} |i - j|^{2H_1 - 2 + (2H_2 - 2)q} \\
\sim c(H_1, H_2, q) N^{2-4H} \sum_{i,j=0; i \neq j}^{N-1} |i - j|^{2H_1 - 2 + (2H_2 - 2)q} \\
= c(H_1, H_2, q) N^{2-4H} \sum_{k=1}^{N-1} (N - k) k^{2H_1 - 2 + (2H_2 - 2)q} \\
= c(H_1, H_2, q) N^{2-4H} \sum_{k=1}^{N-1} k^{2H_1 - 2 + (2H_2 - 2)q} \\
+ c(H_1, H_2, q) N^{2-4H} \sum_{k=1}^{N-1} k^{2H_1 - 1 + (2H_2 - 2)q}.
\]

The sequence \( N^{3-4H} \sum_{k=1}^{N-1} k^{2H_1 - 2 + (2H_2 - 2)q} \) converges to zero when \( N \to \infty \). Indeed, when the series \( \sum_{k=1}^{\infty} k^{2H_1 - 1 + (2H_2 - 2)q} \) is convergent and the sequence \( N^{3-4H} \sum_{k=1}^{N-1} k^{2H_1 - 2 + (2H_2 - 2)q} \) converges to zero since \( H > \frac{3}{4} \). When the same series is divergent, it behaves as \( N^{2H_1 - 2 + (2H_2 - 2)q} + 1 \) and the summand goes to zero because \( 3 - 4H + 2H_1 - 2 + (2H_2 - 2)q + 1 = (2H_2 - 2)(q - 1) < 0 \). The second summand can be treated similarly.

Let us prove now that the term \( R_{N,2} \) converges to zero in \( L^2(\Omega) \) as \( N \to \infty \). We have

\[
\mathbb{E} |R_{N,2}|^2 = c(H_1, H_2, q) N^{2-4H} \sum_{i,j=0}^{N-1} \left( \int_i^{i+1} \int_j^{j+1} |u - v|^{2H_2 - 2} dudv \right)^{q-1} \sum_{i,j=0; i \neq j}^{N-1} |i - j|^{(2H_2 - 2)(q - 1)} \\
\sim c(H_1, H_2, q) N^{2-4H} \sum_{i,j=0; i \neq j}^{N-1} |i - j|^{(2H_2 - 2)(q - 1)}
\]
implies that the series $N_i$ term, which behaves as $\frac{a}{2}$ where we used again the change of summation $i - j = k$ and we noticed that the diagonal term, which behaves as $N^{2-4H}$ converges to zero. The fact that $$(2H_2 - 2)(q - 1) < -1$$ implies that the series $\sum_{k=0}^{N-1} k^{(2H_2-2)(q-1)}$ is convergent and since $H > \frac{3}{4}$ the sequence $N^{3-4H} \sum_{k=0}^{N-1} k^{(2H_2-2)(q-1)}$ goes to zero as $N \to \infty$. The second series is bounded by the first one (since $k \leq N$) and thus it converges to zero. \[ \square \]

In principle, Theorem 2 can be extended to functions $g$ having an infinite series expansion into Hermite polynomials. But in this case, $W_N$ is given by an infinite sum of multiple integrals and it is much more difficult to control the $L^2$ norm of the rest.

**Remark 10**  

a. Let $H_1 + H_2 = 2H > 3$ and $H_1, H_2 > \frac{1}{2}$. Corollary shows that $(\xi_i^{H_1})_{i \in \mathbb{N}}$ and $(\xi_i^{H_2})_{i \in \mathbb{N}}$ are two stationary Gaussian sequences with zero mean and unit variance, and with correlation function $r_1(n) \sim c(H_1)n^{2H_1-2}$, $r_2(n) \sim c(H_1)n^{2H_2-2}$ such that

$$E \left[ \xi_i^{H_1} \xi_j^{H_2} \right] \sim c(H_1, H_2)|i - j|^{H_1+H_2}$$

then

$$N^{1-2H} \sum_{k=1}^{[Nt]} f(\xi_k^{H_1}, \xi_k^{H_2}) - E \left[ f(\xi_k^{H_1}, \xi_k^{H_2}) \right]$$

converges in the sense of finite dimensional distribution to, modulo a constant, a non-symmetric Rosenblatt process with the function $f$ given by $f(x, y) = xy = H_1(x)H_1(y)$. Theorem 2 shows that the result can be extended to function $f$ of the form

$$f(x, y) = H_1(x) \sum_{q=1}^{M} c_q H_q(y)$$

with suitable assumptions on $q, H_1$ and $H_2$.

b. Let us discuss the selfsimilar process with stationary increments from Example 1. This process, denoted by $X = (X_t)_{t \geq 0}$ can be also obtained as a limit in a non-central limit theorem in the following way (see [9], page 127-131). Define $(\xi_k)_{k \in \mathbb{Z}}$ a stationary Gaussian sequence with zero mean and unit variance and with covariance $r_k = E[\xi_0\xi_k] \sim k^{-2\alpha}$. Set $X_k = \xi_k^2 - 1$ and

$$U_m = \sum_{k \in \mathbb{Z}} a_k X_{m-k}$$

with $a_k = 0$ if $k = 0$, $a_k = k^{\beta-1}$ if $k > 0$ and $a_k = -|k|^{-\beta-1}$ if $k < 0$, $\beta > 0$. Assume that $\alpha, \beta$ satisfy the assumptions from Example 1. Then $N^{-\alpha} \sum_{m=1}^{N} U_m$ converges to the process $X$ from Example 1. For the proof of this fact, we refer to [9].
Taking into account the two points above, we can find a mechanism to construct more selfsimilar processes with stationary increment in the second Wiener chaos. For example, consider the sequence $V_N$ given by (11) and from it construct a linear process as $U_m$ above with suitable weight $a_k$. It is expected to find a new selfsimilar process with stationary increments as a limit.

References


