WEAK SYMMETRIC INTEGRALS WITH RESPECT TO THE
FRACTIONAL BROWNIAN MOTION

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Abstract. The aim of this paper is to establish the weak convergence, in the topology
of the Skorohod space, of the $\nu$-symmetric Riemann sums for functionals of the fractional
Brownian motion when the Hurst parameter takes the critical value $H = (4\ell + 2)^{-1}$, where
$\ell = \ell(\nu) \geq 1$ is the largest natural number satisfying $\int_0^1 \alpha^{2j} \nu(d\alpha) = (2j + 1)^{-1}$ for all
$j = 0, \ldots, \ell - 1$. As a consequence, we derive a change-of-variable formula in distribution,
where the correction term is a stochastic integral with respect to a Brownian motion that
is independent of the fractional Brownian motion.

1. Introduction

Suppose that $B^H = \{B^H_t, t \geq 0\}$ is a fractional Brownian motion (fBm) with Hurst
parameter $H \in (0, 1)$, that is, $B^H$ is a centered Gaussian process with covariance given by

$$R(s, t) := \mathbb{E}[B^H_s B^H_t] = \frac{1}{2}(s^{2H} + t^{2H} - |t - s|^{2H}), \quad (1.1)$$

for any $s, t \geq 0$. When $H < \frac{1}{2}$, it is well-known that the integral $\int_0^t g(B^H_s) dB^H_s$ does not exist
in general as a path-wise Riemann-Stieltjes integral. In the pioneering work [5], Gradinaru,
Nourdin, Russo and Vallois proved that this integral can be defined as the limit in probability
of suitable symmetric Riemann sums if the Hurst parameter is not too small. Let us briefly
describe the main contribution of [5].

Let $\nu$ be a symmetric probability measure on $[0, 1]$, meaning that $\nu(A) = \nu(1 - A)$ for
any Borel set $A \subset [0, 1]$. Given a continuous function $g : \mathbb{R} \to \mathbb{R}$, consider the $\nu$-symmetric
Riemann sums of $g(B^H_s)$ in the interval $[0, t]$ given by

$$S_n^\nu(g, t) = \sum_{j=0}^{[nt]-1} \left( B^H_{\frac{j+1}{n}} - B^H_{\frac{j}{n}} \right) \int_0^1 g \left( B^H_{\frac{j}{n}} + \alpha \left( B^H_{\frac{j+1}{n}} - B^H_{\frac{j}{n}} \right) \right) \nu(d\alpha),$$

where $n \geq 1$ is an integer and $[x]$ denotes the integer part of $x$ for any $x \geq 0$. Then, following [5] and providing the limit exists, the $\nu$-symmetric integral is defined as the limit

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in probability of the \( \nu \)-symmetric Riemann sums as \( n \) tends to infinity, namely,
\[
\int_{0}^{t} g(B_{s}^{H})d\nu B_{s}^{H} = \lim_{n \to \infty} S_{n}^{\nu}(g,t).
\]

It is proved in [5] that this integral exists for \( g = f' \) with \( f \in C^{4\ell(\nu)+2}(\mathbb{R}) \), if the Hurst parameter satisfies \( H > \frac{1}{4\ell(\nu)+2} \). Here we denote by \( \ell(\nu) \geq 1 \) the largest positive natural number such that
\[
\int_{0}^{1} \alpha^{2j} \nu(d\alpha) = \frac{1}{2j+1} \quad \forall j = 0, 1, \ldots, \ell(\nu) - 1.
\]

Moreover, in this case the integral \( \int_{0}^{t} f'(B_{s}^{H})d\nu B_{s}^{H} \) satisfies the chain rule
\[
f(B_{t}^{H}) = f(0) + \int_{0}^{t} f'(B_{s}^{H})d\nu B_{s}^{H}.
\]

Basic examples of \( \nu \)-symmetric Riemann sums and integrals are the following:

(i) If \( \nu = \frac{1}{2}\delta_{0} + \frac{1}{2}\delta_{1} \), then \( S_{n}^{\nu} \) are the trapezoidal Riemann sums. In this case \( \ell(\nu) = 1 \) and \( \nu \)-symmetric integrals exist for \( H > \frac{1}{6} \).

(ii) If \( \nu = \frac{1}{6}\delta_{0} + \frac{2}{3}\delta_{1/2} + \frac{1}{3}\delta_{1} \), then \( \ell(\nu) = 2 \). In this case, \( S_{n}^{\nu} \) are the Simpson Riemann sums and \( \nu \)-symmetric integrals exist for \( H > \frac{1}{10} \).

(iii) If \( \nu \) is the Lebesgue measure, then \( \ell(\nu) = \infty \), and \( \nu \)-symmetric integrals exist for any \( H \in (0, 1) \).

The lower bound \( \frac{1}{4\ell(\nu)+2} \) for the Hurst parameter is sharp, in the sense that for \( H = \frac{1}{4\ell(\nu)+2} \) the \( \nu \)-symmetric integral diverges in \( L^{2}(\Omega) \) for \( f(x) = x^{2} \). This has been proved, for the example (i) above, in the references [2] and [5]. The goal of this paper is to show that when \( H = \frac{1}{4\ell(\nu)+2} \), the \( \nu \)-symmetric Riemann sums converge in distribution and, as a consequence, we obtain a change-of-variable formula in law with a correction term which is an Itô stochastic integral with respect to a Brownian motion which is independent of \( B^{H} \). More precisely, the main result is the following theorem.

We say that a function \( f : \mathbb{R} \to \mathbb{R} \) has \textit{moderate growth} if there exist positive constants \( A, B \) and \( \alpha < 2 \) such that \( |f(x)| \leq Ae^{B|x|^\alpha} \) for all \( x \in \mathbb{R} \).

**Theorem 1.1.** Fix a symmetric probability measure \( \nu \) on \( [0, 1] \) with \( \ell := \ell(\nu) < \infty \) and let \( B^{H} = \{B_{t}^{H}, t \geq 0\} \) be a fractional Brownian motion with Hurst parameter \( H = \frac{1}{4\ell+2} \). Consider a function \( f \in C^{20\ell+5}(\mathbb{R}) \) such that \( f \) and its derivatives up to the order \( 20\ell+5 \) have moderate growth. Then,
\[
S_{n}^{\nu}(f', t) \xrightarrow{n \to \infty} f(B_{t}^{H}) - f(0) - c_{\nu} \int_{0}^{t} f^{(2\ell+1)}(B_{s}^{H})dW_{s},
\]
where \( W = \{W_{t}, t \geq 0\} \) is a Brownian motion independent of \( B^{H} \), \( c_{\nu} \) is a constant depending only on \( \nu \), and the convergence holds in the topology of the Skorohod space \( D([0, \infty)) \).

The value of the constant \( c_{\nu} \) in (1.3) is \( c_{\nu} = k_{\nu,\ell}\sigma_{\ell} \), where \( k_{\nu,\ell} \) is defined in (3.2) and \( \sigma_{\ell} \) is given by
\[
\sigma_{\ell}^{2} = 1 + 4^{-\ell} \sum_{j=1}^{\infty} \left( (j+1)\frac{1}{2\ell+1} + (j-1)\frac{1}{2\ell+1} - 2j\frac{1}{2\ell+1} \right)^{2\ell+1}.
\]
The statement of Theorem 1.1 can also be written as the following change-of-variables formula in law:

\[ f(B^H_t) = f(0) + \int_0^t f'(B^H_s) dW^H_s + c_\nu \int_0^t f^{(2\ell+1)}(B^H_s) dW_s. \]

Some particular cases have already been addressed recently in the literature. In the case \( \nu = \frac{1}{2} \delta_0 + \frac{1}{2} \delta_1 \) (trapezoidal Riemann sums), the critical value is \( H = \frac{1}{6} \), and the corresponding version of Theorem 1.1 was proved by Nourdin, Réveillac and Swanson [13]. The convergence results for trapezoidal Riemann sums were extended to a general class of Gaussian processes by Harnett and Nualart in [6]. If \( \nu = \frac{1}{6} \delta_0 + \frac{2}{3} \delta_{\frac{1}{2}} + \frac{1}{6} \delta_1 \) (Simpson Riemann sums), the critical point is \( H = \frac{1}{10} \) and the convergence in law for any fixed time \( t \geq 0 \) was proved by Harnett and Nualart in [8].

For related results in the case of midpoint Riemann sums, we refer to the works by Burdzy and Swanson [1], Nourdin and Réveillac [12] and Harnett and Nualart [7]. In this case the critical value of the Hurst parameter is \( H = \frac{1}{4} \), and the complementary term in the Itô formula involves a second derivative. See also Nourdin [9].

Let us briefly describe the main ideas in the proof of Theorem 1.1. First, using a decomposition of \( f(B^H_t) - f(0) \) based on Taylor’s formula and the properties of the symmetric measure \( \nu \), derived in [5], it turns out that the only nonzero contribution to the limit in law of the \( \nu \)-symmetric Riemann sums \( S^\nu_n(f', t) \) is the term

\[ \sum_{j=0}^{\lfloor nt \rfloor - 1} f^{(2\ell+1)}(B^H_{\frac{j}{n}}) (\Delta_j^\nu B^H)^{2\ell+1}, \]

where we used the notation \( \tilde{B}^H_{\frac{j}{n}} = \frac{1}{2} (B^H_{\frac{j}{n}} + B^H_{\frac{j+1}{n}}) \) and \( \Delta_j^\nu B^H = B^H_{\frac{j+1}{n}} - B^H_{\frac{j}{n}} \). This term is a weighted sum of the odd powers \( (\Delta_j^\nu B^H)^{2\ell+1} \) of the fBm. It is well-known that for \( H = \frac{1}{4\ell+2} \), the sums of these odd powers converge in law to a Gaussian random variable. More precisely, the following stable convergence holds

\[ \left( \sum_{j=0}^{\lfloor nt \rfloor - 1} (\Delta_j^\nu B^H)^{2\ell+1}, B^H_t, t \geq 0 \right) \xrightarrow{\mathcal{L}} \left( \sigma_\ell W_t, B^H_t, t \geq 0 \right), \]

where \( \sigma_\ell \) is defined in (1.4) and in the right-hand side, the process \( W \) is a Brownian motion independent of \( B^H \). The proof of the convergence for a fixed \( t \) follows from the Breuer-Major Theorem (we refer to [11], Chapter 7 and [4] for a proof of this result based on the Fourth Moment theorem). Then the convergence of the weighted sums (1.5) follows from the methodology of small blocks/big blocks used, for instance in the works [4] and [3]. However, unlike these references, the convergence to zero of the reminder term cannot be established using fractional calculus techniques because \( H < \frac{1}{2} \), and it requires the application of integration-by-parts formulas from Malliavin calculus.

The paper is organized as follows. Section 2 contains some preliminaries on the Malliavin calculus and the fractional Brownian motion. Section 3 is devoted to the proof of Theorem 1.1 and in Section 4 we show two basic technical lemmas.
2. Preliminaries

In the next two subsections, we discuss some notions of Malliavin calculus and fractional Brownian motion. Throughout the paper $C$ will denote any positive constant, which may change from one expression to another.

2.1. Elements of Malliavin Calculus. Let $\mathcal{H}$ be a real separable infinite-dimensional Hilbert space and let $X = \{X(h), h \in \mathcal{H}\}$ be an isonormal Gaussian process over $\mathcal{H}$. This means that $X$ is a centered Gaussian family, defined on a complete probability space $(\Omega, \mathcal{F}, P)$, with a covariance structure given by

$$\mathbb{E}[X(h)X(g)] = \langle h, g \rangle_{\mathcal{H}}, \quad h, g \in \mathcal{H}.$$ 

We assume that $\mathcal{F}$ is the $\sigma$-algebra generated by $X$.

For any integer $q \geq 1$, let $\mathcal{H}^\otimes q$ and $\mathcal{H}^\odot q$ denote, respectively, the $q$th tensor product and the $q$th symmetric tensor product of $\mathcal{H}$.

Let $\{e_n, n \geq 1\}$ be a complete orthonormal system in $\mathcal{H}$. Given $f \in \mathcal{H}^\otimes p$, $g \in \mathcal{H}^\odot q$ and $r \in \{0, \ldots, p \wedge q\}$, the $r$-th order contraction of $f$ and $g$ is the element of $\mathcal{H}^\odot (p+q-2r)$ defined by

$$f \otimes_r g = \sum_{i_1, \ldots, i_r = 1}^{\infty} \langle f, e_{i_1} \otimes \ldots \otimes e_{i_r} \rangle_{\mathcal{H}^\otimes r} \otimes \langle g, e_{i_1} \otimes \ldots \otimes e_{i_r} \rangle_{\mathcal{H}^\odot r}, \quad (2.1)$$

where $f \otimes_0 g = f \otimes g$ and, for $p = q$, $f \otimes_q g = \langle f, g \rangle_{\mathcal{H}^\odot q}$. Notice that $f \otimes_r g$ is not necessarily symmetric. We denote its symmetrization by $f\overset{\circ}{\otimes}_r g \in \mathcal{H}^\odot (p+q-2r)$.

Let $\mathcal{H}_q$ denote the $q$th Wiener chaos of $X$, that is, the closed linear subspace of $L^2(\Omega)$ generated by the random variables $\{H_q(X(h)), h \in \mathcal{H}, \|h\|_{\mathcal{H}} = 1\}$, where $H_q$ is the $q$th Hermite polynomial defined by

$$H_q(x) = (-1)^q e^{x^2/2} \frac{d^q}{dx^q} \left(e^{-x^2/2}\right). \quad (2.2)$$

For $q \geq 1$, let $I_q(\cdot)$ denote the generalized Wiener-Itô multiple stochastic integral. It is known that the map

$$I_q(h^\otimes q) = H_q(X(h)) \quad (2.3)$$

provides a linear isometry between $\mathcal{H}^\otimes q$ (equipped with the modified norm $\sqrt{q!}\|\cdot\|_{\mathcal{H}^\otimes q}$) and $\mathcal{H}_q$ (equipped with the $L^2(\Omega)$ norm). For $q = 0$, we set by convention $\mathcal{H}_0 = \mathbb{R}$ and $I_0$ equal to the identity map.

Multiple stochastic integrals satisfy the following product formula. Let $p, q \geq 1$ positive integers. Let $f \in \mathcal{H}^\otimes p$ and $g \in \mathcal{H}^\odot q$. Then,

$$I_p(f)I_q(g) = \sum_{z=0}^{p \wedge q} \binom{p}{z} \binom{q}{z} I_{p+q-2z}(f \otimes_z g), \quad (2.4)$$

where $\otimes_z$ is the contraction operator defined in (2.1).

From the hypercontractivity property of the Ornstein-Uhlenbeck semigroup, it is well-known that all $L^r(\Omega)$-norms, $r > 1$, are equivalent on each Wiener chaos. In particular, for
any real number \( r \geq 2 \), any integer \( p \geq 2 \) and any \( f \in \mathcal{S}^{\otimes p} \), we have
\[
\| I_p(f) \|_{L^r(\Omega)} \leq C_{r,p} \| I_p(f) \|_{L^2(\Omega)} = C_{r,p} \sqrt{p!} \| f \|_{\mathcal{S}^{\otimes p}}.
\] (2.5)

Let \( \mathcal{S} \) be the set of all smooth and cylindrical random variables of the form
\[
F = g(X(\phi_1), \ldots, X(\phi_n)),
\]
where \( n \geq 1 \), \( g : \mathbb{R}^n \to \mathbb{R} \) is an infinitely differentiable function with compact support, and \( \phi_i \in \mathcal{S} \). The Malliavin derivative of \( F \) with respect to \( X \) is the element of \( L^2(\Omega; \mathcal{S}) \) defined as
\[
DF = \sum_{i=1}^{n} \frac{\partial g}{\partial x_i} (X(\phi_1), \ldots, X(\phi_n)) \phi_i.
\]
By iteration, we can define the \( q \)th derivative \( D^q F \) for every \( q \geq 2 \), which is an element of \( L^2(\Omega; \mathcal{S}^{\otimes q}) \).

For any integer \( q \geq 1 \) and any real number \( p \geq 1 \), let \( \mathbb{D}^{q,p} \) denote the closure of \( \mathcal{S} \) with respect to the norm \( \| \cdot \|_{\mathbb{D}^{q,p}} \), defined as
\[
\| F \|_{\mathbb{D}^{q,p}}^p \mathbb{E}[|F|^p] + \sum_{i=1}^{q} \mathbb{E} \left( \| D^i F \|_{\mathbb{H}^{\otimes i}}^{p} \right).
\]
More generally, for any Hilbert space \( V \), we denote by \( \mathbb{D}^{q,p}(V) \) the corresponding Sobolev space of \( V \)-valued random variables.

The Malliavin derivative \( D \) fulfills the following chain rule. If \( \varphi : \mathbb{R}^n \to \mathbb{R} \) is continuously differentiable with bounded partial derivatives and if \( F = (F_1, \ldots, F_n) \) is a vector of elements of \( \mathbb{D}^{1,2} \), then \( \varphi(F) \in \mathbb{D}^{1,2} \) and
\[
D\varphi(F) = \sum_{i=1}^{n} \frac{\partial \varphi}{\partial x_i}(F) DF_i.
\]

We denote by \( \delta \) the Skorohod integral, also called the divergence operator, which is the adjoint of the operator \( D \). More precisely, a random element \( u \in L^2(\Omega; \mathcal{S}) \) belongs to the domain of \( \delta \), denoted by \( \text{Dom} \delta \), if and only if, for any \( F \in \mathbb{D}^{1,2} \), we have
\[
\mathbb{E}(\langle DF, u \rangle_{\mathcal{S}}) \leq c_u \| F \|_{L^2(\Omega)},
\]
where \( c_u \) is a constant depending only on \( u \). If \( u \in \text{Dom} \delta \), then the random variable \( \delta(u) \) is defined by the duality relationship
\[
\mathbb{E}(F \delta(u)) = \mathbb{E}(\langle DF, u \rangle_{\mathcal{S}}).
\]
This is called the Malliavin integration by parts formula and it holds for every \( F \in \mathbb{D}^{1,2} \).

For \( q \geq 1 \), the multiple Skorohod integral is defined iteratively as
\[
\delta^q(u) = \delta(\delta^{q-1}(u)),
\]
with \( \delta^0(u) = u \). From this definition, we have
\[
\mathbb{E}(F \delta^q(u)) = \mathbb{E}(\langle DF, u \rangle_{\mathcal{S}^{\otimes q}}),
\] (2.6)
for any \( u \in \text{Dom} \delta^q \) and any \( F \in \mathbb{D}^{q,2} \). Moreover, \( \delta^q(h) = I_q(h) \) for any \( h \in \mathcal{S}^{\otimes q} \). We refer to [14] for a detailed account on the Malliavin calculus for an arbitrary isonormal Gaussian process.
2.2. Fractional Brownian motion. Let $B^H = \{B^H_t, t \geq 0\}$ denote a fractional Brownian motion with Hurst parameter $H$. Namely, $B^H$ is a centered Gaussian process, defined on a complete probability space $(\Omega, \mathcal{F}, P)$ with covariance given by (1.1). We assume that $\mathcal{F}$ is generated by $B^H$. Along the paper we suppose that $H < \frac{1}{2}$.

We denote by $\mathcal{E}$ the set of $\mathbb{R}$-valued step functions on $[0, \infty)$. Let $\mathcal{H}$ be the Hilbert space defined as the closure of $\mathcal{E}$ with respect to the scalar product

$$\langle 1_{[0,t]}, 1_{[0,s]} \rangle_{\mathcal{H}} = R(s,t).$$

The mapping $1_{[0,t]} \rightarrow B^H_t$ can be extended to a linear isometry between the Hilbert space $\mathcal{H}$ and the Gaussian space spanned by $B^H$. In this way $\{B^H(h), h \in \mathcal{H}\}$ is an isonormal Gaussian process as in Section 2.1.

Recall the notation $	ilde{B}^H_j = \frac{1}{2} (B^H_j + B^H_{j+1})$ and $\Delta^n B^H_j = B^H_{j+1} - B^H_j$. Moreover, we set

$$\partial_j^n = 1_{[j\frac{n}{T}, (j+1)\frac{n}{T}]}$$

and

$$\tilde{\varepsilon}_t = \frac{1}{2} (\varepsilon_t + \varepsilon_{t+1}).$$

The fractional Brownian motion with Hurst parameter $H$ satisfies

$$\mathbb{E}[(\Delta^n B^H)^2] = \langle \partial_j^n, \partial_j^n \rangle_{\mathcal{H}} = n^{-2H}. \quad (2.7)$$

Moreover, using the fact that the function $x \rightarrow x^{2H}$ is concave for $H < \frac{1}{2}$, for any $t \geq 0$ and any integer $j \geq 0$, we obtain

$$|\mathbb{E}[(\Delta^n B^H)B^H_t]| = |\langle \partial_j^n, \varepsilon_t \rangle_{\mathcal{H}}| \leq n^{-2H}. \quad (2.8)$$

The following lemma has been proved in [8, Lemma 2.6].

**Lemma 2.1.** Let $H < \frac{1}{2}$ and let $n \geq 2$ be an integer. Then, there exists a constant $C$ not depending on $T$ such that:

a) For any $t \in [0, T]$,

$$\sum_{j=0}^{[nT]-1} |\langle \partial_j^n, \varepsilon_t \rangle_{\mathcal{H}}| \leq C [nT]^{2H} n^{-2H}. \quad (2.9)$$

b) For any integers $r \geq 1$ and $0 \leq i \leq [nT] - 1$,

$$\sum_{j=0}^{[nT]-1} |\langle \partial_j^n, \partial_i^n \rangle_{\mathcal{H}}^r| \leq C n^{-2rH}, \quad (2.10)$$

and consequently

$$\sum_{j,i=0}^{[nT]-1} |\langle \partial_j^n, \partial_i^n \rangle_{\mathcal{H}}^r| \leq C [nT] n^{-2rH}. \quad (2.11)$$

The next result provides useful estimates when we compare two partitions. Its proof is based on computing telescopic sums.
Lemma 2.2. We fix two integers \( n > m \geq 2 \), and for any \( j \geq 0 \), we define \( k := k(j) = \sup\{i \geq 0 : \frac{k}{m} \leq \frac{j+1}{n}\} \). The following inequalities hold true for some constant \( C \) depending only on \( T \):

\[
\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \partial^{\frac{j}{n}}, C^{k(j)} \rangle \right| \leq C n^{1-2H}, \tag{2.11}
\]

\[
\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \partial^{\frac{j}{n}}, \tilde{C}^{k(j)} - C^{k(j)} \rangle \right| \leq C n^{1-2H}. \tag{2.12}
\]

and, for any \( 0 \leq i \leq \lfloor nT \rfloor - 1 \),

\[
\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \partial^{\frac{j}{n}}, \tilde{C}^{k(j)} - C^{k(j)} \rangle \right| \leq C n^{2H}. \tag{2.13}
\]

Proof. Let us first show (2.11). We can write

\[
\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \partial^{\frac{j}{n}}, C^{k(j)} \rangle \right| = \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \mathbb{E} \left[ \left( \frac{B_{j+1}^{H}}{n} - \frac{B_{j}^{H}}{n} \right) \frac{B_{k(j)}^{H}}{m} \right] \right|
\]

\[
= \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \left( \frac{j+1}{n} \right)^{2H} - \left( \frac{j}{n} \right)^{2H} - \frac{j+1}{n} - \frac{k(j)}{m} \right| + \frac{j}{n} - \frac{k(j)}{m} \right|^{2H} \right|
\]

\[
\leq \frac{1}{2} \frac{n^{-2H}}{\lfloor nT \rfloor - 1} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left( (j+1)^{2H} - j^{2H} \right)
\]

\[
+ \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left[ \left( \frac{j+1}{n} - \frac{k(j)}{m} \right)^{2H} - \left( \frac{j}{n} - \frac{k(j)}{m} \right)^{2H} \right].
\]

The first term is a telescopic sum and it is easy to show that

\[
\frac{1}{2} \frac{n^{-2H}}{\lfloor nT \rfloor - 1} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left( (j+1)^{2H} - j^{2H} \right) = \frac{1}{2} \frac{n^{-2H}}{\lfloor nT \rfloor} (\lfloor nT \rfloor)^{2H} \leq C \leq C n^{1-2H}.
\]

For the second term, observe that, for a fixed \( k = 0, \ldots, \lfloor mT \rfloor + 1 \), the sum of the terms for which \( k(j) = k \) is telescopic and is bounded by a constant times \( n^{-2H} \leq m^{-2H} \). Summing over all possible values of \( k \), we obtain the desired bound \( C n^{1-2H} \).

The inequality (2.12) is an immediate consequence of (2.11) and the following easy fact:

\[
\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \partial^{\frac{j}{n}}, \tilde{C}^{k(j)} \rangle \right| = \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \mathbb{E} \left[ \left( \frac{B_{j+1}^{H}}{n} - \frac{B_{j}^{H}}{n} \right) \left( \frac{B_{k(j)}^{H}}{m} + \frac{B_{k(j)}^{H}}{m} \right) \right] \right|
\]

\[
= \frac{n^{-2H}}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left( (j+1)^{2H} - j^{2H} \right) = \frac{1}{2} \frac{n^{-2H}}{\lfloor nT \rfloor} (\lfloor nT \rfloor)^{2H} \leq C \leq C n^{1-2H}.
\]
Let us now proceed with the proof of (2.13). We can write

$$\sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \langle \frac{\partial \xi}{\partial t}, \xi - \xi_{k(m)} \rangle \right|_2$$

$$= \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \mathbb{E} \left[ \left( B_{k+1}^H - B_+^H \right) \left( B_{\frac{k+1}{m}}^H + B_{\frac{k}{m}}^H - 2 B_{\frac{k}{m}}^H \right) \right] \right|$$

$$\leq \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \mathbb{E} \left[ \left( B_{k+1}^H - B_+^H \right) \left( B_{\frac{k+1}{m}}^H - B_{\frac{k}{m}}^H \right) \right] \right|$$

$$+ \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} \left| \mathbb{E} \left[ \left( B_{k+1}^H - B_+^H \right) \left( B_{\frac{k+1}{m}}^H - B_{\frac{k}{m}}^H \right) \right] \right|$$

$$=: A_1 + A_2.$$

For the term $A_1$ we have

$$A_1 = \frac{1}{2} \sum_{j=0}^{\lfloor nT \rfloor - 1} |H_j|,$$

where

$$H_j = \left| \frac{i}{n} - \frac{j}{n} \right|^{2H} \left| \frac{i}{n} - \frac{j + 1}{n} \right|^{2H} + \left| \frac{k(i)}{m} - \frac{j + 1}{n} \right|^{2H} - \left| \frac{k(i)}{m} - \frac{j}{n} \right|^{2H}.$$

Taking into account that $\frac{k(i)}{m} \leq \frac{i}{n}$, it follows that, for $j \geq i$

$$H_j = \left( \frac{j}{n} - \frac{i}{n} \right)^{2H} - \left( \frac{j + 1}{n} - \frac{i}{n} \right)^{2H} + \left( \frac{j + 1}{n} - \frac{k(i)}{m} \right)^{2H} - \left( \frac{j}{n} - \frac{k(i)}{m} \right)^{2H}$$

$$= 2H \int_{0}^{\frac{1}{n}} \left[ \left( \frac{j}{n} + x - \frac{k(i)}{m} \right)^{2H-1} - \left( \frac{j}{n} + x - \frac{i}{n} \right)^{2H-1} \right] dx \leq 0.$$

On the other hand, if $j_0$ is the largest integer $j \geq 0$ such that $\frac{i + 1}{n} \leq \frac{k(i)}{m}$, then, for $j \leq j_0$,

$$H_j = \left( \frac{i}{n} - \frac{j}{n} \right)^{2H} - \left( \frac{i}{n} - \frac{j + 1}{n} \right)^{2H} + \left( \frac{k(i)}{m} - \frac{j + 1}{n} \right)^{2H} - \left( \frac{k(i)}{m} - \frac{j}{n} \right)^{2H}$$

$$= -2H \int_{0}^{\frac{1}{n}} \left[ \left( \frac{k(i)}{m} - \frac{j}{n} - x \right)^{2H-1} - \left( \frac{i}{n} - \frac{j}{n} - x \right)^{2H-1} \right] dx \leq 0.$$

Consider the decomposition

$$A_1 = \frac{1}{2} \left( \sum_{j=0}^{j_0} |H_j| + \sum_{j=j_0+1}^{i-1} |H_j| + \sum_{j=i}^{\lfloor nT \rfloor - 1} |H_j| \right) = \frac{1}{2} (A_{11} + A_{12} + A_{13}).$$
For the terms $A_{11}$ and $A_{13}$, we obtain, respectively

\[ A_{11} = \sum_{j=0}^{j_0} (-H_j) \]
\[ = \left( \frac{i}{n} - \frac{j_0 + 1}{n} \right)^{2H} - \left( \frac{k(i) - j_0 + 1}{m} \right)^{2H} - \left( \frac{i}{n} \right)^{2H} + \left( \frac{k(i)}{m} \right)^{2H} \]
\[ \leq 2 \left( \frac{i}{n} - \frac{k(i)}{m} \right)^{2H} \leq Cm^{-2H} \]

and

\[ A_{13} = \sum_{j=i}^{\lfloor nT \rfloor - 1} (-H_j) \]
\[ = \left( \frac{\lfloor nT \rfloor - i}{n} \right)^{2H} - \left( \frac{\lfloor nT \rfloor - k(i)}{m} \right)^{2H} + \left( \frac{i}{n} - \frac{k(i)}{m} \right)^{2H} \]
\[ \leq \left( \frac{i}{n} - \frac{k(i)}{m} \right)^{2H} \leq m^{-2H}. \]

Finally, for the term $A_{12}$, we have

\[ A_{12} \leq \sum_{j=j_0+1}^{i-1} \left| \left( \frac{i}{n} - \frac{j}{n} \right)^{2H} - \left( \frac{i}{n} - \frac{j+1}{n} \right)^{2H} \right| \]
\[ + \sum_{j=j_0+1}^{i-1} \left| \left( \frac{j+1}{n} - \frac{k(i)}{m} \right)^{2H} - \left( \frac{j}{n} - \frac{k(i)}{m} \right)^{2H} \right| \]
\[ =: A_{121} + A_{122}. \]

The term $A_{121}$ is a telescopic sum which produces a contribution of the form

\[ \left( \frac{i - j_0 - 1}{n} \right)^{2H} \leq Cm^{-2H} \]

and the term $A_{122}$ can be bounded as follows

\[ A_{122} \leq \left| \frac{j_0 + 2}{n} - \frac{k(i)}{m} \right|^{2H} + \left| \frac{j_0 + 1}{n} - \frac{k(i)}{m} \right|^{2H} + \sum_{j=j_0+2}^{i-1} \left[ \left( \frac{j + 1}{n} - \frac{k(i)}{m} \right)^{2H} - \left( \frac{j}{n} - \frac{k(i)}{m} \right)^{2H} \right] \]
\[ \leq Cm^{-2H} + \left( \frac{i}{n} - \frac{k(i)}{m} \right)^{2H} - \left( \frac{j_0 + 2}{n} - \frac{k(i)}{m} \right)^{2H} \leq Cm^{-2H}. \]

The term $A_2$ can be treated in a similar way. This completes the proof. \( \square \)

We will use the following lemma.

**Lemma 2.3.** For any odd integer $r \geq 1$, we have

\[ (\Delta_j^n B^H)^r = \sum_{u=0}^{\lfloor r \rfloor} C_{r,u} n^{-2uH} I_{r-2u} (\partial_j^{\otimes r-2u}), \]
where \( C_{r,u} \) are some integers.

**Proof.** By (2.7), we have \( \| \Delta_j^n B^H \|_{L^2(\Omega)} = n^{-H} \). For any integer \( q \geq 1 \), we recall (see (2.2)) that \( H_q(x) \) denotes the Hermite polynomial of degree \( q \). Using an inductive argument coming from the relation \( H_{q+1}(x) = xH_q(x) - qH_{q-1}(x) \), it follows that

\[
x^r = \sum_{u=0}^{\left\lfloor \frac{r}{2} \right\rfloor} C_{r,u} H_{r-2u}(x),
\]

(2.14)

where \( C_{r,u} \) is an integer. Applying (2.3) to \( h = n^H \partial_\frac{\pi}{n} \), that is, \( X(h) = \Delta_j^n B^H / \| \Delta_j^n B^H \|_{L^2(\Omega)} = n^H \Delta_j^n B^H \), we can write

\[
H_r(n^H \Delta_j^n B^H) = I_r(n^r H \partial_\frac{\pi}{\pi}).
\]

(2.15)

Substituting (2.15) into (2.14), yields

\[
n^r H \left( \Delta_j^n B^H \right)^r = \sum_{u=0}^{\left\lfloor \frac{r}{2} \right\rfloor} C_{r,u} I_r(n^{(r-2u)H} \partial_\frac{\pi}{\pi}^{2r-2u}),
\]

which implies the desired result. \( \square \)

### 3. Proof of Theorem 1.1

We recall that \( \ell = \ell(\nu) \) is defined by (1.2). The first ingredient of the proof is the following development, established in [5], based on Taylor’s formula and the properties of the measure \( \nu \)

\[
f(b) = f(a) + (b-a) \int_0^1 f'(a + \alpha (b-a)) \nu(d\alpha)
\]

\[
+ \sum_{h=\ell}^{2\ell} k_{\nu,h} f^{(2h+1)} \left( \frac{a+b}{2} \right) (b-a)^{2h+1} + (b-a)^{4\ell+2} C(a,b),
\]

(3.1)

where \( a, b \in \mathbb{R} \) and \( C(a,b) \) is a continuous function such that \( C(a,a) = 0 \). The constants \( k_{\nu,h} \) are given by

\[
k_{\nu,h} = \frac{1}{(2h)!} \left[ \frac{1}{(2h+1)4^h} - \int_0^1 \left( \alpha - \frac{1}{2} \right)^{2h} \nu(d\alpha) \right].
\]

(3.2)
Applying equality (3.1) to \( a = B^H_n \) and \( b = B^H_{1+n} \) and using the notation \( \tilde{B}^H_n = \frac{1}{2}(B^H_n + B^H_{1+n}) \) and \( \Delta_j^H B^H = B^H_{j+1} - B^H_j \), yields

\[
f(B^H_{\lfloor nt \rfloor}) - f(0) = \sum_{j=0}^{[nt]-1} \Delta_j^H B^H \int_0^1 f'(B^H_n + \alpha \Delta_j^H B^H) \nu(d\alpha) \\
+ \frac{2\ell}{[nt]!} \sum_{j=0}^{[nt]-1} \sum_{h=\ell} \tilde{B}^H_j (\Delta_j^H B^H)^{2h+1} \\
+ \sum_{j=0}^{[nt]-1} C(B^H_n, B^H_{1+n})(\Delta_j^H B^H)^{4\ell+2},
\]

which can be written as

\[
f(B^H_{\lfloor nt \rfloor}) - f(0) = S_n^\nu(f', t) + \sum_{h=\ell} \Phi_n^h(t) + R_n(t),
\]

(3.3)

where, for each \( h = \ell, \ldots, 2\ell, \)

\[
\Phi_n^h(t) = \sum_{j=0}^{[nt]-1} k_{v, h} f^{(2h+1)}(\tilde{B}^H_j (\Delta_j^H B^H)^{2h+1} 
\]

(3.4)

and

\[
R_n(t) = \sum_{j=0}^{[nt]-1} C(B^H_n, B^H_{1+n})(\Delta_j^H B^H)^{4\ell+2}.
\]

Let us consider the convergence of each term in the decomposition (3.3). First we will show that the term \( R_n(t) \) converges to zero in probability, uniformly in compact sets. In fact, for any \( T > 0, K, \epsilon > 0 \), we can write

\[
P \left( \sup_{0 \leq t \leq T} |R_n(t)| > \epsilon \right) \leq P \left( \sup_{s,t \in [0,T]} |C(B^H_s, B^H_t)| > \frac{1}{K} \right) + P \left( \sum_{j=0}^{[nT]-1} (\Delta_j^H B^H)^{4\ell+2} > K \epsilon \right).
\]

(3.5)

Taking into account that \( H = \frac{1}{4\ell+2} \) and using (2.7), we can write, with \( \mu_k \) denoting the \( k \)th moment of the standard Gaussian,

\[
P \left( \sum_{j=0}^{[nT]-1} (\Delta_j^H B^H)^{4\ell+2} > K \epsilon \right) \leq \frac{\mu_{4\ell+2}}{K^\epsilon} \frac{nT}{\epsilon} \leq \frac{T \mu_{4\ell+2}}{K^\epsilon}.
\]

(3.6)

From (3.5) and (3.6), letting first \( n \to \infty \) and then \( K \to \infty \) it follows that for any \( \epsilon > 0 \) and \( T > 0, \)

\[
\lim_{n \to \infty} P \left( \sup_{0 \leq t \leq T} |R_n(t)| > \epsilon \right) = 0.
\]
On the other hand, by Lemma 4.1, the terms $\Phi^h_n$ with $h = \ell + 1, \ldots, 2\ell$ converge to zero in the topology of $D([0, \infty))$ and do not contribute to the limit. As a consequence, the proof of Theorem 1.1 follows from the next proposition.

**Proposition 3.1.** Under the assumptions of Theorem 1.1, one has

$$
\Phi^\ell_n(t) = \sum_{j=0}^{\lfloor nt \rfloor - 1} f^{(2\ell+1)} \left( B^{H}_{\frac{j}{n}} \right) \left( \Delta_{\frac{j}{n}} B^H \right)^{2\ell+1} \frac{\mathcal{L}}{n} \frac{\sigma_\ell}{n} \int_0^t f^{(2\ell+1)}(B^{H}_s) \, dW_s, \quad (3.7)
$$

where $W = \{W_t, t \geq 0\}$ is a Brownian motion independent of $B^H$, $\sigma_\ell$ is the constant defined in (1.4), and the convergence holds in the topology of the Skorohod space $D([0, \infty))$.

**Proof.** In order to show Proposition 3.1, we will first prove that the sequence of processes $\{\Phi^\ell_n(t), t \geq 0\}$ is tight in $D([0, \infty))$, and then that their finite dimensional distributions converge to those of

$$
\left\{ \sigma_\ell \int_0^t f^{(2\ell+1)}(B^{H}_s) \, dW_s, t \geq 0 \right\}.
$$

Notice that the tightness of the sequence $\Phi^\ell_n$ is a consequence of Lemma 4.1. Indeed, this lemma implies that for any $0 \leq s < t \leq T$, there exist a constant depending on $T$, such that

$$
\mathbb{E} \left[ |\Phi^\ell_n(t) - \Phi^\ell_n(s)|^4 \right] \leq C \sum_{N=2}^4 \left( \frac{|nt| - |ns|}{n} \right)^N.
$$

It remains to show the convergence of the finite-dimensional distributions. Fix a finite set of points $0 \leq t_1 < \cdots < t_d \leq T$. We want to show the following convergence in law, as $n$ tends to infinity:

$$
(\Phi^\ell_n(t_1), \ldots, \Phi^\ell_n(t_d)) \xrightarrow{\mathcal{L}}_{n \to \infty} (Y_1, \ldots, Y_d), \quad (3.8)
$$

where

$$
Y_i = \sigma_\ell \int_0^{t_i} f^{(2\ell+1)}(B^{H}_s) \, dW_s, \quad i = 1, \ldots, d,
$$

$W = \{W_t, t \geq 0\}$ is a Brownian motion independent of $B^H$, and $\sigma_\ell$ is the constant defined in (1.4).

Taking into account the convergence (1.6), the main ingredient in the proof of the convergence (3.8) is the methodology based on the small blocks/big blocks (see, for instance, [4]). This method consists in considering two integers $2 \leq m < n$ and let first $n$ tend to infinity and later $m$ tend to infinity. For any $k \geq 0$ we define the set

$$
I_k = \{ j \in \{0, \ldots, \lfloor nt \rfloor - 1 \} : \frac{k}{m} \leq \frac{j}{n} < \frac{k+1}{m} \}. 
$$
The basic ingredient in this approach is the decomposition
\[
\Phi_n^\ell (t_i) = \sum_{k=0}^{\lfloor m t_i \rfloor} \sum_{j \in I_k} f^{(2\ell+1)}(B^H_{m}) (\Delta_j B^H)^{2\ell+1} + \sum_{k=0}^{\lfloor m t_i \rfloor} \sum_{j \in I_k} \left[ f^{(2\ell+1)}(\frac{\Delta_j B^H}{2}) - f^{(2\ell+1)}(B^H_{m}) \right] (\Delta_j B^H)^{2\ell+1} =: A_{n,m}^{(1,i)} + A_{n,m}^{(2,i)}.
\]
From Lemma 4.2 with \( r = 2\ell + 1 \) and \( \phi = f^{(2\ell+1)} \), we can write, for any \( q > 2 \),
\[
\mathbb{E}[ (A_{n,m}^{(2,i)})^2 ] \leq C \sup_{0 \leq w \leq 3(2\ell+1)} \sup_{0 \leq j \leq \lfloor nT \rfloor - 1} \| f^{(w)}(\frac{\Delta_j B^H}{2}) - f^{(w)}(B^H_{m}) \|_{L^q(\Omega)}^2 + C \sup_{0 \leq w \leq 3(2\ell+1)} \sup_{0 \leq j \leq \lfloor nT \rfloor - 1} \| f^{(w)}(\frac{\Delta_j B^H}{2}) - f^{(w)}(B^H_{m}) \|_{L^q(\Omega)}^2 \times (1 + n^{2H-1} m^{2-4H}) \times \left( 1 + \sup_{0 \leq w \leq 3(2\ell+1)} \sup_{s \in [0,T]} \sup_{|t-s| \leq \frac{m}{n}} \left\| f^{(w)}(B^H_s + \frac{B^H_{\frac{s+t}{2}}}{2}) - f^{(w)}(B^H_t) \right\|_{L^q(\Omega)}^2 \right),
\]
where \( k := k(j) = \sup \{ i \geq 0 : \frac{i}{m} \leq \frac{j}{n} \} \). This implies
\[
\limsup_{n \to \infty} \mathbb{E}[ (A_{n,m}^{(2,i)})^2 ] \leq C \left( m^{-2H} + \sup_{0 \leq w \leq 3(2\ell+1)} \sup_{s \in [0,T]} \sup_{|t-s| \leq \frac{m}{n}} \left\| f^{(w)}(B^H_s) - f^{(w)}(B^H_t) \right\|_{L^2(\Omega)}^2 \right),
\]
which converges to zero as \( m \) tends to infinity.

On the other hand, from (1.6) we deduce that the vector \( (A_{1,n,m}, \ldots A_{d,n,m}) \) converges in law, as \( n \) tends to infinity, to the vector with components
\[
\sigma_t \sum_{k=0}^{\lfloor m t_i \rfloor} f^{(2\ell+1)}(B^H_{m}) (W_{k+1} - W_k),
\]
i = 1, \ldots, d, where \( W \) is a Brownian motion independent of \( B^H \). Each of these components converges in \( L^2(\Omega) \) to the stochastic integral \( \sigma_t \int_0^t f^{(2\ell+1)}(B^H_s) \, dW_s \), as \( m \) tends to infinity. This completes the proof of the theorem. \( \square \)

4. APPENDIX

This section is devoted to state and prove a couple of technical lemmas. The first lemma is the basic ingredient to show that the sequence of processes \( \Phi_n^\ell \) are tight and the processes \( \Phi_n^h \) for \( h = \ell + 1, \ldots, 2\ell \) converge to zero in \( D([0,\infty)) \). For this we need to estimate the fourth moment of the increments of the processes \( \Phi_n^h \).
Lemma 4.1. Consider the processes $\Phi_n^h$, $h = 1, \ldots, 2\ell$ defined in (3.4). Then, for any $0 \leq s < t \leq T$ we have

$$
\mathbb{E} \left[ |\Phi_n^h(t) - \Phi_n^h(s)|^4 \right] \leq C \sum_{N=2}^{4} \left( |nt| - |ns| \right)^N n^{-2NH(2h+1)},
$$

where the constant $C$ depends only on $T$.

Proof. For any $0 \leq s < t \leq T$ we can write

$$
\mathbb{E} \left[ |\Phi_n^h(t) - \Phi_n^h(s)|^4 \right] = \sum_{j_1, j_2, j_3, j_4 = [ns]}^{[nt] - 1} \mathbb{E} \left[ \prod_{i=1}^{4} f^{(2h+1)}(\tilde{B}_n^{H}(\Delta_{j_i}^n B^H)^{2h+1}) \right].
$$

By Lemma 2.3 we obtain

$$
(\Delta_{j_i}^n B^H)^{2h+1} = \sum_{u=0}^{h} C_{2h+1,u} n^{-2uH} I_{2h+1-2u}(\partial_{\frac{n}{n}}^{(2h+1-2u)}),
$$

which leads to

$$
\prod_{i=1}^{4} (\Delta_{j_i}^n B^H)^{2h+1} = \sum_{u_1, u_2, u_3, u_4=0}^{h} C_{h,u} n^{-2|u|H} \prod_{i=1}^{4} I_{2h+1-2u_i}(\partial_{\frac{n}{n}}^{(2h+1-2u_i)}),
$$

where $C_{h,u}$ is a constant depending on $h$ and the vector $u = (u_1, u_2, u_3, u_4)$ and we use the notation $|u| = u_1 + u_2 + u_3 + u_4$. To simplify the notation we write $2h + 1 - u_i = v_i$ for $i = 1, 2, 3, 4$. The product formula for multiple stochastic integrals allows us to write

$$
\prod_{i=1}^{4} \left( I_v(\partial_{\frac{n}{n}}^{\alpha_i v_i}) \right) = \sum_{\alpha \in \Lambda} C_{\alpha} \prod_{1 \leq i < k \leq 4} \langle \partial_{\frac{n}{n}}^{\alpha_i v_i}, \partial_{\frac{n}{n}}^{\alpha_k v_k} \rangle
$$

$$
\times I_{|v|-2|\alpha|} \left( \partial_{\frac{n}{n}}^{v_1 \alpha_1} \otimes \partial_{\frac{n}{n}}^{v_2 \alpha_2} \otimes \partial_{\frac{n}{n}}^{v_3 \alpha_3} \otimes \partial_{\frac{n}{n}}^{v_4 \alpha_4} \right),
$$

where $|v| = v_1 + v_2 + v_3 + v_4 = 8h + 4 - |u|$, $\Lambda$ is the set of all multiindices $\alpha = (\alpha_{12}, \alpha_{13}, \alpha_{14}, \alpha_{23}, \alpha_{24}, \alpha_{34})$ with $\alpha_{ik} \geq 0$, such that

$$
\alpha_{12} + \alpha_{13} + \alpha_{14} \leq v_1,
\alpha_{12} + \alpha_{23} + \alpha_{24} \leq v_2,
\alpha_{13} + \alpha_{23} + \alpha_{34} \leq v_3,
\alpha_{14} + \alpha_{24} + \alpha_{34} \leq v_4.
$$

For any $j = (j_1, j_2, j_3, j_4)$, $[ns] \leq j_i \leq [nt] - 1$, we set

$$
Y_j = \prod_{i=1}^{4} f^{(2h+1)}(\tilde{B}_n^{H}),
$$

and

$$
h_{j,a,v} = \partial_{\frac{n}{n}}^{a_1 \alpha_1} \otimes \partial_{\frac{n}{n}}^{a_2 \alpha_2} \otimes \partial_{\frac{n}{n}}^{a_3 \alpha_3} \otimes \partial_{\frac{n}{n}}^{a_4 \alpha_4}.
$$
Applying the duality formula (2.6) we obtain
\[ \mathbb{E} \left[ Y_j I_{|v| - 2|\alpha|} (h_j, \alpha, \nu) \right] = \mathbb{E} \left[ \langle D^{\|v| - 2|\alpha|} Y_j, h_j, \alpha, \nu \rangle \right]. \]

Therefore, we have shown the following formula
\[ \mathbb{E} \left[ |\Phi_n(t) - \Phi_n(s)|^4 \right] = \sum_j \sum_u C_{h,u} n^{-2|u|} \sum_{\alpha \in \Lambda} C_{\alpha} \times \left( \prod_{1 \leq i < k \leq 4} \langle \partial_{\frac{\alpha}{n}}, \partial_{\frac{v}{n}} \rangle_{\mathcal{H}} \right) \mathbb{E} \left[ \langle D^{\|v| - 2|\alpha|} Y_j, h_j, \alpha, \nu \rangle \right], \]

where the components of \( j \) satisfy \( |ns| \leq j_i \leq |nt| - 1 \) and \( 0 \leq u_i \leq h \). Finally, the inner product \( \langle D^{\|v| - 2|\alpha|} Y_j, h_j, \alpha, \nu \rangle \) can be expressed in the form
\[ \sum_{\beta \in \Gamma} \Phi_{\beta} \prod_{1 \leq i, k \leq 4} \langle \partial_{\frac{\alpha}{n}}, \partial_{\frac{v}{n}} \rangle_{\mathcal{H}}^{\beta_{ik}}, \]

where \( \beta = (\beta_{ik})_{1 \leq i, k \leq 4} \) is a matrix with nonnegative entries such that
\[ \sum_{k=1}^{4} \beta_{1k} = v_1 - \alpha_{12} - \alpha_{13} - \alpha_{14}, \]
\[ \sum_{k=1}^{4} \beta_{2k} = v_2 - \alpha_{12} - \alpha_{23} - \alpha_{24}, \]
\[ \sum_{k=1}^{4} \beta_{3k} = v_3 - \alpha_{13} - \alpha_{23} - \alpha_{34}, \]
\[ \sum_{k=1}^{4} \beta_{4k} = v_4 - \alpha_{14} - \alpha_{24} - \alpha_{34}. \]

Notice that \( |\beta| = \sum_{i,k=1}^{4} \beta_{ik} = |v| - 2|\alpha| \). The random variables \( \Phi_{\beta} \) are linear combination of products of the form \( \prod_{i=1}^{4} f^{(w_i)} (B^{H}_{\frac{\alpha}{n}}) \), with \( 2h + 1 \leq w_i \leq 2h + 1 + |v| - 2|\alpha| \). This leads to the following estimate
\[ \mathbb{E} \left[ |\Phi_n(t) - \Phi_n(s)|^4 \right] \leq C \sum_j \sum_u n^{-2|u|} \sum_{\alpha \in \Lambda} \sum_{\beta \in \Gamma} \prod_{1 \leq i < k \leq 4} \langle \partial_{\frac{\alpha}{n}}, \partial_{\frac{v}{n}} \rangle_{\mathcal{H}}^{\beta_{ik}} \prod_{1 \leq i, k \leq 4} \langle \partial_{\frac{\alpha}{n}}, \partial_{\frac{v}{n}} \rangle_{\mathcal{H}}^{\beta_{ik}}. \]

Consider the decomposition of the above sum as follows
\[ \mathbb{E} \left[ |\Phi_n(t) - \Phi_n(s)|^4 \right] \leq C \left( A_n^{(1)} + A_n^{(2)} + A_n^{(3)} \right), \]

where \( A_n^{(1)} \) contains all the terms such that at least two components of \( \alpha \) are nonzero, \( A_n^{(2)} \) contains all the terms such that one component of \( \alpha \) is nonzero and the others vanish, and \( A_n^{(3)} \) contains all the terms such that all the components of \( \alpha \) are zero.
Step 1. Let us first estimate $A_n^{(1)}$. Without any loss of generality, we can assume that $\alpha_{12} \geq 1$ and $\alpha_{13} \geq 1$. From (2.9) with $r = 1$, we obtain

$$\sum_{j_1=\lfloor ns \rfloor}^{\lfloor nt \rfloor - 1} \left| \langle \partial_{\frac{\alpha_{12}}{n}} \partial_{\frac{\alpha_{13}}{n}} \rangle \right| \leq C n^{-2H}$$

(4.1)

and

$$\sum_{j_3=\lfloor ns \rfloor}^{\lfloor nt \rfloor - 1} \left| \langle \partial_{\frac{\alpha_{12}}{n}} \partial_{\frac{\alpha_{13}}{n}} \rangle \right| \leq C n^{-2H}.$$

We estimate each of the remaining factors by $n^{-2H}$. In this way, we obtain a bound of the form

$$A_n^{(1)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^2 n^{-2H(\|u\| + |\alpha| + |\beta|)}.$$

Taking into account that $|\alpha| \leq \frac{1}{2} |v|$, we have

$$|u| + |\alpha| + |\beta| = |u| + |\alpha| + |v| - 2|\alpha| = |u| + |v| - |\alpha| \geq |u| + \frac{|v|}{2} = 4h + 2 - \frac{|u|}{2} \geq 4h + 2,$$

and, as a consequence,

$$A_n^{(1)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^2 n^{-4H(2h+1)}.$$

(4.2)

Step 2. For the term $A_n^{(2)}$, we can assume that $\alpha_{12} \geq 1$ and all the other components of $\alpha$ vanish. In this case, we still have the inequality (4.1). Then, we estimate each of the remaining factors by $n^{-2H}$. In this way, we obtain a bound of the form

$$A_n^{(2)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^3 n^{-2H(\|u\| + |\alpha| + |\beta|)}.$$

Taking into account that $|\alpha| = \alpha_{12} \leq v_1 = 2h + 1 - u_1 \leq 2h + 1$,

$$|u| + |\alpha| + |\beta| = |u| + |\alpha| + |v| - 2|\alpha| = |u| + |v| - |\alpha| \geq |u| + |v| - 2h - 1 = 6h + 3,$$

and, as a consequence, we obtain

$$A_n^{(2)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^3 n^{-6H(2h+1)}.$$

(4.3)

Step 3. Estimating all terms by $n^{-2H}$, we get

$$A_n^{(3)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^4 n^{-2H(\|u\| + |\beta|)}.$$

We have

$$|u| + |\beta| = |u| + |v| = 8h + 4,$$

and, as a consequence, we obtain

$$A_n^{(3)} \leq C \left( \lfloor nt \rfloor - \lfloor ns \rfloor \right)^4 n^{-8H(2h+1)}.$$

(4.4)

In conclusion, from (4.2), (4.3) and (4.4), we obtain the desired estimate. This completes the proof of the lemma. □
The second lemma provides a bound for the residual term in the application of the small blocks / big blocks technique and it is a variation of [8, Lemma 3.2]. Its proof is based on the techniques of Malliavin calculus. As before for two integers \( n > m \geq 2 \), for any \( j \geq 0 \) we define \( k := k(j) = \sup \{ i \geq 0 : \frac{i}{m} \leq \frac{j}{n} \} \).

**Lemma 4.2.** Let \( r = 1, 3, 5, \ldots \) and \( n > m \geq 2 \) be two integers. Let \( \phi : \mathbb{R} \to \mathbb{R} \) be a \( C^{2r} \) function such that \( \phi \) and all derivatives up to order \( 2r \) have moderate growth, and let \( B^H = \{ B^H_t, t \geq 0 \} \) be a fBm with Hurst parameter \( H < \frac{1}{2} \). Then, for any \( q > 2 \) and any \( T > 0 \),

\[
\sup_{t \in [0, T]} \mathbb{E} \left[ \left( \sum_{j=0}^{[nt]-1} \phi(\tilde{B}^H_{\frac{n}{j}}) - \phi(B^H_{\frac{n}{m}}) \right) (\Delta^n B^H)^r \right] \leq C \Gamma_{m,n} n^{1-2rH},
\]

where \( C \) is a positive constant depending on \( q, r, H \) and \( T \), and

\[
\Gamma_{m,n} := \sup_{0 \leq w \leq 2r} \sup_{0 \leq i,j \leq \lfloor nT \rfloor - 1} \left\| \phi^{(w)}(\tilde{B}^H_{\frac{n}{j}}) - \phi^{(w)}(B^H_{\frac{n}{m}}) \right\|^2_{L^q(\Omega)} + \sup_{0 \leq w \leq 2r} \sup_{0 \leq i,j \leq \lfloor nT \rfloor - 1} \left\| \phi^{(w)}(\tilde{B}^H_{\frac{n}{j}}) \right\|^2_{L^2(\Omega)} (m^{-2H} + n^{2H-1} m^{2-4H})
\]

\[
+ \sup_{0 \leq w \leq 2r} \sup_{0 \leq i,j \leq \lfloor nT \rfloor - 1} \left\| \phi^{(w)}(\tilde{B}^H_{\frac{n}{j}}) \right\|_{L^2(\Omega)} \left\| \phi^{(w)}(\tilde{B}^H_{\frac{n}{j}}) - \phi^{(w)}(B^H_{\frac{n}{m}}) \right\|_{L^2(\Omega)} \times (1 + n^{2H-1} m^{2-4H}).
\]

**Proof.** The proof is based in the methodology used to show Lemma 3.2 in [8]. To simplify notation, let \( Y_j(\phi) := \phi(\tilde{B}^H_{\frac{n}{j}}) - \phi(B^H_{\frac{n}{m}}) \), and set

\[
I_t := \mathbb{E} \left[ \left( \sum_{j=0}^{[nt]-1} Y_j(\phi) (\Delta^n B^H)^r \right) \right].
\]

From Lemma 2.3 we obtain

\[
I_t = \sum_{u,v=0}^{\lfloor \frac{t}{2} \rfloor} C_{r,u} C_{r,v} n^{-2H(u+v)} \sum_{i,j=0}^{[nt]-1} \mathbb{E} \left[ Y_i(\phi) Y_j(\phi) I_{r-2u}(\partial_{\frac{n}{j}}^{\otimes r-2u}) I_{r-2v}(\partial_{\frac{n}{j}}^{\otimes r-2v}) \right].
\]

\[
\leq C \sum_{u,v=0}^{\lfloor \frac{t}{2} \rfloor} n^{-2H(u+v)} \sum_{i,j=0}^{[nt]-1} \mathbb{E} \left[ Y_i(\phi) Y_j(\phi) I_{r-2u}(\partial_{\frac{n}{j}}^{\otimes r-2u}) I_{r-2v}(\partial_{\frac{n}{j}}^{\otimes r-2v}) \right].
\]
Then we apply the product formula (2.4) in order to develop the product of two multiple divergence operators and we end up with

\[ I_t \leq C \sum_{u,v=0}^{\left[{\frac{r}{2}}\right]} (r-2u) \times (r-2v) n^{-2H(u+v)} \sum_{i,j=0}^{\left[{\frac{nT}{2}}\right]-1} \left| \mathbb{E} \left[ Y_i(\phi)Y_j(\phi) \right] \right| \]

\[ \times I_{2r-2(u+v)-2z} \left( \partial_{\frac{\phi}{r}}^{r-2u-z} \otimes \partial_{\frac{n}{r}}^{r-2v-z} \right) \left( \partial_{\frac{\phi}{n}}^{2u}, \partial_{\frac{n}{n}}^{2v} \right) \phi_j \right] \]

\[ = C \sum_{u,v=0}^{\left[{\frac{r}{2}}\right]} n^{-2H(u+v)} \sum_{i,j=0}^{\left[{\frac{nT}{2}}\right]-1} \left| \mathbb{E} \left[ Y_i(\phi)Y_j(\phi) I_{2r-2(u+v)} \left( \partial_{\frac{\phi}{r}}^{r-2u} \otimes \partial_{\frac{n}{r}}^{r-2v} \right) \right] \right| \]

\[ + C \sum_{u,v=0}^{\left[{\frac{r}{2}}\right]} n^{-2H(u+v)} \sum_{i,j=0}^{\left[{\frac{nT}{2}}\right]-1} \left| \mathbb{E} \left[ Y_i(\phi)Y_j(\phi) \right] \right| \]

\[ \times I_{2r-2(u+v)-2z} \left( \partial_{\frac{\phi}{r}}^{r-2u-z} \otimes \partial_{\frac{n}{r}}^{r-2v-z} \right) \left( \partial_{\frac{\phi}{n}}^{2u}, \partial_{\frac{n}{n}}^{2v} \right) \phi_j \right] \]

\[ =: C(D_1 + D_2). \]

We first study term \( D_2 \), that is when \( z \geq 1 \). On one hand, from the estimate (2.5), we get

\[ \left\| I_{2r-2(u+v)-2z} \left( \partial_{\frac{\phi}{r}}^{r-2u-z} \otimes \partial_{\frac{n}{r}}^{r-2v-z} \right) \right\|_{L^q(\Omega)} \leq C \left( \left\| \partial_{\frac{\phi}{n}}^{2u} \right\|_{L^2(\Omega)} \left\| \partial_{\frac{n}{n}}^{2v} \right\|_{L^2(\Omega)} \right) \]

\[ = C \left\| \partial_{\frac{\phi}{n}}^{2r-2(u+v)-2z} \rightsquigarrow \phi_j \right\|_{L^2(\Omega)} \]

\[ = C n^{-2H(r-u-v-z)}. \quad (4.5) \]

On the other hand, using (2.10), we obtain

\[ \sum_{i,j=0}^{\left[{\frac{nT}{2}}\right]-1} \left| \left( \partial_{\frac{\phi}{n}}^{2u}, \partial_{\frac{n}{n}}^{2v} \right) \right| \leq C n^{1-2zH}. \quad (4.6) \]

Thus, from (4.5) and (4.6) and using Hölder’s inequality, we deduce that the term \( D_2 \) is bounded by

\[ D_2 \leq C \sum_{u,v=0}^{\left[{\frac{r}{2}}\right]} n^{-2H(u+v)} \sup_{0 \leq j \leq \left[{\frac{nT}{2}}\right]-1} \left\| Y_j(\phi) \right\|_{L^q(\Omega)}^2 n^{-2H(r-u-v-z)} n^{1-2zH} \]

\[ \leq C \sup_{0 \leq j \leq \left[{\frac{nT}{2}}\right]-1} \left\| Y_j(\phi) \right\|_{L^q(\Omega)}^2 n^{1-2rH}. \]

Now, let us study term \( D_1 \), that is when \( z = 0 \). By (2.6) we have

\[ \left| \mathbb{E} \left[ Y_i(\phi)Y_j(\phi) I_{2r-2(u-v)} \left( \partial_{\frac{\phi}{r}}^{r-2u} \otimes \partial_{\frac{n}{r}}^{r-2v} \right) \right] \right| \]

\[ = \left| \mathbb{E} \left[ \left( D_{\phi}^{2r-2(u-v)}(Y_i(\phi)Y_j(\phi)), \partial_{\frac{\phi}{n}}^{r-2u} \otimes \partial_{\frac{n}{r}}^{r-2v} \right) \right] \right|. \]

Write \( s = 2(r-u-v) \). By definition of Malliavin derivative and Leibniz rule, \( D_{\phi}^{s-\left[{\frac{nT}{2}}\right]-1}(Y_i(\phi)Y_j(\phi)) \) consists of terms of the form \( D_{\phi}^{s-\left[{\frac{nT}{2}}\right]-1}(Y_i(\phi)Y_j(\phi)) \), where \( J \) is a subset of \( \{1, \ldots, s\} \), \( |J| \) denotes the cardinality of \( J \) and \( u_J = (u_i)_{i \in J} \). Without loss of generality, we may fix \( J \) and
assume that \( a = |J| \geq 1 \). By our assumptions on \( \phi \) and the definition of Malliavin derivative, we know that

\[
D^a(Y_i(\phi)) = \phi^{(a)}(\tilde{B}_H^a) \tilde{e}^{a} - \phi^{(a)}(B_H^{(m)}) \tilde{e}^{a} = Y_i(\phi^{(a)}) \tilde{e}^{a} + \phi^{(a)}(\tilde{B}_H) \tilde{e}^{a},
\]

where recall that \( k = \{ i : \frac{j}{m} \leq \frac{i}{n} \} \), and, for each \( a \leq 2r \), we have \( D^a(Y_i(\phi)) \in L^2(\Omega; \mathfrak{J}^{\otimes a}) \). Setting \( b = s - |J| = s - a \) and with a slight abuse of notation, it follows that

\[
\mathbb{E} \left[ \left( D_{u_j}^{a}(Y_i(\phi)) D_{u_{j'}}^{b}(Y_j(\phi)), \partial_{B_{H}^{(a)}}^{2(r-2u)} \partial_{B_{H}^{(b)}}^{2(r-2v)} \right) \right] \\
\leq \| Y_i(\phi^{(a)}) \|_{L^2(\Omega)} \| Y_j(\phi^{(b)}) \|_{L^2(\Omega)} \left| \left( \tilde{e}^{a}, \tilde{e}^{b} \right) \right| \| \partial_{B_{H}^{(a)}}^{2(r-2u)} \partial_{B_{H}^{(b)}}^{2(r-2v)} \|_{\mathfrak{J}^{\otimes 4}} \\
+ \| Y_i(\phi^{(a)}) \|_{L^2(\Omega)} \| \phi^{(b)}(\tilde{B}_H^{(a)}) \|_{L^2(\Omega)} \left| \left( \tilde{e}^{a}, \tilde{e}^{b} \right) \right| \| \partial_{B_{H}^{(a)}}^{2(r-2u)} \partial_{B_{H}^{(b)}}^{2(r-2v)} \|_{\mathfrak{J}^{\otimes 4}} \\
+ \| \phi^{(a)}(\tilde{B}_H^{(a)}) \|_{L^2(\Omega)} \| \phi^{(b)}(\tilde{B}_H^{(b)}) \|_{L^2(\Omega)} \left| \left( \tilde{e}^{a}, \tilde{e}^{b} \right) \right| \| \partial_{B_{H}^{(a)}}^{2(r-2u)} \partial_{B_{H}^{(b)}}^{2(r-2v)} \|_{\mathfrak{J}^{\otimes 4}} \\
=: D_{11} + D_{12} + D_{13} + D_{14}.
\]

Consider first the term \( D_{11} \). By (2.8), we have either

\[
D_{11} \leq C \left| \left( \tilde{e}^{k(1)}, \partial_{\frac{m}{n}} \right) \right| n^{-2H(a+b-1)} \sup_{0 \leq u \leq 2r} \sup_{0 \leq j \leq |nT| - 1} \| Y_j(\phi^{(u)}) \|_{L^2(\Omega)}^2
\]

or

\[
D_{11} \leq C \left| \left( \tilde{e}^{k(1)}, \partial_{\frac{m}{n}} \right) \right| n^{-2H(a+b-1)} \sup_{0 \leq u \leq 2r} \sup_{0 \leq j \leq |nT| - 1} \| Y_j(\phi^{(u)}) \|_{L^2(\Omega)}^2.
\]

By Lemma 2.1.a

\[
\sum_{j=0}^{|nT|-1} \left| \left( \tilde{e}^{k(j)}, \partial_{\frac{m}{n}} \right) \right| \leq C
\]

and by (2.11),

\[
\sum_{j=0}^{|nT|-1} \sum_{j=0}^{|nT|-1} \left| \left( \tilde{e}^{k(j)}, \partial_{\frac{m}{n}} \right) \right| \left| \left( \tilde{e}^{k(j)}, \partial_{\frac{m}{n}} \right) \right| \leq Cm^{2-4H}.
\]
As a consequence, inequalities (4.7) and (4.8) imply
\[
\sum_{u,v=0}^{nT-1} n^{-2H(u+v)} \sum_{i,j=0}^{nT-1} D_{11} \leq C \sup_{0\leq w \leq 2r} \sup_{0\leq j \leq [nT]-1} \|Y_j(\phi(w))\|_{L^2(\Omega)}^2 \sum_{u,v=0}^{nT-1} n^{-2H(u+v+a+b-1)}
\]
\[
+ C \sup_{0\leq w \leq 2r} \sup_{0\leq j \leq [nT]-1} \|Y_j(\phi(w))\|_{L^2(\Omega)}^2 \sum_{u,v=0}^{nT-1} n^{-2H(u+v+a+b-1)} n^{2H} m^{2-4H} n^{1-2rH},
\]
where we used that \(u + v + a + b - 1 = 2r - (u + v) - 1 \geq r\), since \(u + v + 1 \leq 2 \left\lceil \frac{r}{2} \right\rceil + 1 = r\) for any odd integer \(r\).

We apply the same calculation to \(D_{12}\) and \(D_{13}\), and we similarly obtain that
\[
\sum_{u,v=0}^{nT-1} n^{-2H(u+v)} \sum_{i,j=0}^{nT-1} (D_{12} + D_{13}) \leq C \sup_{0\leq w \leq 2r} \sup_{0\leq j \leq [nT]-1} \|\phi(w)(\tilde{B}^H_n)\|_{L^2(\Omega)} \sup_{0\leq j \leq [nT]-1} \|Y_j(\phi(w))\|_{L^2(\Omega)} \times (1 + n^{1-2H} m^{2-4H}) n^{1-2rH}.
\]

Now we study term \(D_{14}\). Inequalities (2.12) and (2.13) state that
\[
\sum_{j=0}^{[nT]-1} \left| \left\langle \tilde{\varepsilon}_{\frac{j}{n}} - \varepsilon_{\frac{j}{n}}, \partial_{\frac{j}{n}} \right\rangle_{\Omega} \right| \leq C m^{-2H} \quad \text{and} \quad \sum_{i=0}^{[nT]-1} \left| \left\langle \tilde{\varepsilon}_{\frac{i}{n}} - \varepsilon_{\frac{i}{n}}, \partial_{\frac{i}{n}} \right\rangle_{\Omega} \right| \leq C m^{1-2H}.
\]
Then, with the same reasoning used for \(D_{11}\), we obtain
\[
\sum_{u,v=0}^{nT-1} n^{-2H(u+v)} \sum_{i,j=0}^{nT-1} D_{14} \leq C \sup_{0\leq w \leq 2r} \sup_{0\leq j \leq [nT]-1} \|\phi(w)(\tilde{B}^H_n)\|_{L^2(\Omega)} \times (m^{-2H} + n^{1-2H} m^{2-4H}) n^{1-2rH}.
\]

The proof is now concluded. \(\square\)

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