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BAHADUR REPRESENTATION OF SAMPLE QUANTILES FOR
FUNCTIONAL OF GAUSSIAN DEPENDENT SEQUENCES UNDER A
MINIMAL ASSUMPTION

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We obtain a Bahadur representation for sample quantiles of nonlinear functional of Gaussian sequences with correlation function decreasing as $k^{-\alpha}$ for some $\alpha > 0$. This representation is derived under a minimal assumption.

1 Introduction

We consider the problem of obtaining a Bahadur representation of sample quantiles in a certain dependence context. Before stating in what a Bahadur representation consists, let us specify some general notation. Given some random variable Y , $F(\cdot) = F_Y(\cdot)$ is referred as the cumulative distribution function of Y , $\xi(p) = \xi_Y(p)$ for some $0 < p < 1$ as the quantile of order p . If $F(\cdot)$ is absolutely continuous with respect to Lebesgue measure, the probability density function is denoted by $f(\cdot) = f_Y(\cdot)$. Based on the observation of a vector $\mathbf{Y} = (Y(1), \dots, Y(n))$ of n random variables distributed as Y , the sample cumulative distribution function and the sample quantile of order p are respectively denoted by $\widehat{F}_Y(\cdot; \mathbf{Y})$ and $\widehat{\xi}_Y(p; \mathbf{Y})$ or simply by $\widehat{F}(\cdot; \mathbf{Y})$ and $\widehat{\xi}(p; \mathbf{Y})$.

Let $\mathbf{Y} = (Y(1), \dots, Y(n))$ a vector of n i.i.d. random variables such that $F''(\xi(p))$ exists and is bounded in a neighborhood of $\xi(p)$ and such that $F'(\xi(p)) > 0$, Bahadur proved that as $n \rightarrow +\infty$,

$$\widehat{\xi}(p) - \xi(p) = \frac{p - \widehat{F}(p)}{f(\xi(p))} + r_n,$$

¹*Key words and phrases.* Gaussian processes, Bahadur representation of sample quantiles, Hermite expansions.

with $r_n = \mathcal{O}_{a.s.}(n^{-3/4} \log(n)^{3/4})$ where a sequence of random variables U_n is said to be $\mathcal{O}_{a.s.}(v_n)$ if U_n/v_n is almost surely bounded. Kiefer obtained the exact rate $n^{-3/4} \log \log(n)^{3/4}$. Under an Assumption on $F(\cdot)$ which is quite similar to the one done by Bahadur, extensions of above results to dependent random variables have been pursued in Sen and Ghosh (1972) for ϕ -mixing variables, in Yoshihara (1995) for strongly mixing variables, and recently in Wu (2005) for short-range and long-range dependent linear processes, following works of Hesse (1990) and Ho and Hsing (1996). Finally, such a representation has been obtained by Coeurjolly (2007) for nonlinear functional of Gaussian sequences with correlation function decreasing as $k^{-\alpha}$ for some $\alpha > 0$.

Ghosh (1971) proposed in the i.i.d. case a much simpler proof of Bahadur's result which suffices for many statistical applications. He established under a weaker assumption on $F(\cdot)$ ($F'(\cdot)$ exists and is bounded in a neighborhood of $\xi(p)$ and $f(\xi(p)) > 0$) that the remainder term satisfies $r_n = o_p(n^{-1/2})$, which means that $n^{1/2}r_n$ tends to 0 in probability. This result is sufficient for example to establish a central limit theorem for the sample quantile. Our goal is to extend Ghosh's result to nonlinear functional of Gaussian sequences with correlation function decreasing as $k^{-\alpha}$. The Bahadur representation is presented in Section 2 and is applied to a central limit theorem for the sample quantile. Proofs are deferred in Section 3.

2 Main result

Let $\{Y(i)\}_{i=1}^{+\infty}$ be a stationary (centered) gaussian process with variance 1, and correlation function $\rho(\cdot)$ such that, as $i \rightarrow +\infty$

$$|\rho(i)| \sim i^{-\alpha} \tag{1}$$

for some $\alpha > 0$.

Let us recall some background on Hermite polynomials: the Hermite polynomials form an orthogonal system for the Gaussian measure and are in particular such that $\mathbf{E}(H_j(Y)H_k(Y)) = j! \delta_{j,k}$, where Y is referred to a standard Gaussian variable. For some measurable function $g(\cdot)$ defined on \mathbb{R} such that $\mathbf{E}(g(Y)^2) < +\infty$, the following expansion holds

$$g(t) = \sum_{j \geq \tau} \frac{c_j}{j!} H_j(t) \quad \text{with} \quad c_j = \mathbf{E}(g(Y)H_j(Y)),$$

where the integer τ defined by $\tau = \inf \{j \geq 0, c_j \neq 0\}$, is called the Hermite rank of the function g . Note that this integer plays an important role. For example, it is related to the correlation of $g(Y_1)$ and $g(Y_2)$, for Y_1 and Y_2 two standard gaussian variables with correlation ρ , since $\mathbf{E}(g(Y_1)g(Y_2)) = \sum_{k \geq \tau} \frac{(c_k)^2}{k!} \rho^k = \mathcal{O}(\rho^\tau)$.

Our result is based on the assumption that $F'_{g(Y)}(\cdot)$ exists and is bounded in a neighborhood of $\xi(p)$. This is achieved if the function $g(\cdot)$ satisfies the following assumption (see *e.g.* Dacunha-Castelle and Dufflo (1982), p.33).

Assumption $\mathbf{A}(\xi(p))$: there exist U_i , $i = 1, \dots, L$, disjoint open sets such that U_i contains a unique solution to the equation $g(t) = \xi_{g(Y)}(p)$, such that $F'_{g(Y)}(\xi(p)) > 0$ and such that g is a \mathcal{C}^1 -diffeomorphism on $\cup_{i=1}^L U_i$.

Note that this assumption allows us to obtain

$$F'_{g(Y)}(\xi_{g(Y)}(p)) = f_{g(Y)}(\xi_{g(Y)}(p)) = \sum_{i=1}^L \frac{\phi(g_i^{-1}(t))}{g'(g_i^{-1}(t))},$$

where $g_i(\cdot)$ is the restriction of $g(\cdot)$ on U_i and where $\phi(\cdot)$ is referred to the probability density function of a standard Gaussian variable.

Now, define, for some real u , the function $h_u(\cdot)$ by:

$$h_u(t) = \mathbf{1}_{\{g(t) \leq u\}}(t) - F_{g(Y)}(u). \tag{2}$$

We denote by $\tau(u)$ the Hermite rank of $h_u(\cdot)$. For the sake of simplicity, we set $\tau_p = \tau(\xi_{g(Y)}(p))$. For some function $g(\cdot)$ satisfying Assumption $\mathbf{A}(\xi(p))$, we denote by

$$\bar{\tau}_p = \inf_{\gamma \in \cup_{i=1}^L g(U_i)} \tau(\gamma), \tag{3}$$

that is the minimal Hermite rank of $h_u(\cdot)$ for u in a neighborhood of $\xi_{g(Y)}(p)$. Denote also by $c_j(u)$ the j -th Hermite coefficient of the function $h_u(\cdot)$.

Theorem 1 *Under Assumption $\mathbf{A}(\xi(p))$, the following result holds as $n \rightarrow +\infty$*

$$\widehat{\xi}(p; \mathbf{g}(\mathbf{Y})) - \xi_{g(Y)}(p) = \frac{p - \widehat{F}(\xi_{g(Y)}(p); \mathbf{g}(\mathbf{Y}))}{f_{g(Y)}(\xi_{g(Y)}(p))} + o_{\mathbb{P}}(r_n(\alpha, \bar{\tau}_p)), \tag{4}$$

where $\mathbf{g}(\mathbf{Y}) = (g(Y(1)), \dots, g(Y(n)))$, for $i = 1, \dots, n$ and where the sequence $(r_n(\alpha, \bar{\tau}_p))_{n \geq 1}$ is defined by

$$r_n(\alpha, \bar{\tau}_p) = \begin{cases} n^{-1/2} & \text{if } \alpha \bar{\tau}_p > 1, \\ n^{-1/2} \log(n)^{1/2} & \text{if } \alpha \bar{\tau}_p = 1, \\ n^{-\alpha \bar{\tau}_p / 2} & \text{if } \alpha \bar{\tau}_p < 1. \end{cases} \tag{5}$$

Remark 1 *The sequence $r_n(\alpha, \bar{\tau}_p)$ is related to the behaviour short-range or long-range dependent behaviour of the sequence $h_u(Y(1)), \dots, h_u(Y(n))$ for u in a neighborhood of $\xi(p)$. More precisely, it corresponds to the asymptotic behaviour of the sequence*

$$\left(\frac{1}{n} \sum_{|i| < n} \rho(i)^{\bar{\tau}_p} \right)^{1/2}.$$

Corollary 2 *Under Assumption $\mathbf{A}(\xi(p))$, then the following convergence in distribution hold as $n \rightarrow +\infty$*

(i) *if $\alpha \bar{\tau}_p > 1$*

$$\sqrt{n} \left(\widehat{\xi}(p; \mathbf{g}(\mathbf{Y})) - \xi_{g(Y)}(p) \right) \xrightarrow{d} \mathcal{N}(0, \sigma_p^2), \quad (6)$$

where

$$\sigma_p^2 = \frac{1}{f(p)^2} \sum_{i \in \mathbb{Z}} \sum_{j \geq \bar{\tau}_p} \frac{c_j(p)^2}{j!} \rho(i)^j \quad \text{with } f(p) = f_{g(Y)}(\xi_{g(Y)}(p)) \text{ and } c_j(p) = c_j(\xi_{g(Y)}(p)).$$

(ii) *if $\alpha \bar{\tau}_p < 1$*

$$n^{\alpha \bar{\tau}_p / 2} \left(\widehat{\xi}(p; \mathbf{g}(\mathbf{Y})) - \xi_{g(Y)}(p) \right) \xrightarrow{d} \frac{c_{\bar{\tau}_p}(p)}{\bar{\tau}_p! f(p)} Z_{\bar{\tau}_p}, \quad (7)$$

where

$$Z_{\bar{\tau}_p} = K(\bar{\tau}_p, \alpha) \int'_{\mathbb{R}^{\bar{\tau}_p}} \frac{\exp(i(\lambda_1 + \dots + \lambda_{\bar{\tau}_p})) - 1}{i(\lambda_1 + \dots + \lambda_{\bar{\tau}_p})} \prod_{j=1}^{\bar{\tau}_p} |\lambda_j|^{(\alpha-1)/2} \tilde{B}(d\lambda_j)$$

and

$$K(\bar{\tau}_p, \alpha) = \left(\frac{(1 - \alpha \bar{\tau}_p / 2)(1 - \alpha \bar{\tau}_p)}{\bar{\tau}_p! (2\Gamma(\alpha) \sin(\pi(1 - \alpha)/2))^{\bar{\tau}_p}} \right)^{1/2}.$$

The measure \tilde{B} is a Gaussian complex measure and the symbol \int' means that the domain of integration excludes the hyperdiagonals $\{\lambda_i = \pm \lambda_j, i \neq j\}$.

The proof of this result is omitted since it is a direct application of Theorem 1 and general limit theorems adapted to nonlinear functional of Gaussian sequences, *e.g.* Breuer and Major (1983) and Dehling and Taquq (1989).

3 Proofs

3.1 Auxiliary Lemma

Lemma 3 For every $j \geq 1$ and for all positive sequence $(u_n)_{n \geq 1}$ such that $u_n \rightarrow 0$, as $n \rightarrow +\infty$, we have, under Assumption $\mathbf{A}(\xi(\mathbf{p}))$

$$I = \int_{\mathbb{R}} H_j(t) \phi(t) \mathbf{1}_{\{|g(t) - \xi_{g(Y)}(p)| \leq u_n\}} dt \sim u_n \kappa_j, \quad (8)$$

where κ_j is defined, for every $j \geq 1$, by

$$\kappa_j = \begin{cases} -2 \sum_{i=1}^L \frac{\phi'(g_i^{-1}(\xi(p)))}{g'(g_i^{-1}(\xi(p)))} & \text{if } j = 1, \\ 2(-1)^j \sum_{i=1}^L \frac{\phi^{(j-2)}(g_i^{-1}(\xi(p)))}{g'(g_i^{-1}(\xi(p)))} & \text{if } j > 1. \end{cases} \quad (9)$$

Proof. Under Assumption $\mathbf{A}(\xi(\mathbf{p}))$, there exists $n_0 \in \mathbb{N}$ such that for all $n \geq n_0$,

$$I = \sum_{i=1}^L I_i \quad \text{with} \quad I_i = \int_{U_i} H_j(t) \phi(t) \mathbf{1}_{\{\xi(p) - u_n \leq g(t) \leq \xi(p) + u_n\}} dt. \quad (10)$$

Assume without loss of generality that the restriction of $g(\cdot)$ on U_i (denoted by $g_i(\cdot)$) is an increasing function, we have

$$\begin{aligned} I_i &= \int_{U_i} H_j(t) \phi(t) \mathbf{1}_{\{\xi(p) - u_n \leq g(t) \leq \xi(p) + u_n\}} dt \\ &= \int_{g_i^{-1}(\xi(p) - u_n)}^{g_i^{-1}(\xi(p) + u_n)} H_j(t) \phi(t) dt \\ &= \begin{cases} \phi(m_{i,n}) - \phi(M_{i,n}) = (m_{i,n} - M_{i,n}) & \text{if } j = 1 \\ (-1)^j (\phi^{(j-1)}(M_{i,n}) - \phi^{(j-1)}(m_{i,n})) & \text{if } j > 1, \end{cases} \end{aligned}$$

where $M_{i,n} = g_i^{-1}(\xi(p) + u_n)$ and $m_{i,n} = g_i^{-1}(\xi(p) - u_n)$. Then, there exists $\omega_{n,i,j} \in [m_{i,n}, M_{i,n}]$ for every $j \geq 1$ such that

$$I_i = \begin{cases} (m_{i,n} - M_{i,n}) \phi^{(1)}(\omega_{n,i,1}) & \text{if } j = 1 \\ (-1)^j (M_{i,n} - m_{i,n}) \phi^{(j-2)}(\omega_{n,i,j}) & \text{if } j > 1. \end{cases},$$

Under Assumption $\mathbf{A}(\xi(\mathbf{p}))$, we have, as $n \rightarrow +\infty$

$$\omega_{n,i,j} \sim g_i^{-1}(\xi(p)) \quad \text{and} \quad M_{i,n} - m_{i,n} \sim 2u_n \frac{1}{g'(g_i^{-1}(\xi(p)))},$$

which ends the proof. \blacksquare

3.2 Proof of Theorem 1

For the sake of simplicity, we set $\widehat{\xi}(p) = \widehat{\xi}(p; \mathbf{g}(\mathbf{Y}))$, $\xi(p) = \xi_{g(Y)}(p)$, $\widehat{F}(\cdot) = \widehat{F}(\cdot; \mathbf{g}(\mathbf{Y}))$, $F(\cdot) = F_{g(Y)}(\cdot)$ et $f(\cdot) = f_{g(Y)}(\cdot)$ and $r_n = r_n(\alpha, \bar{\tau}_p)$. Define,

$$V_n = r_n^{-1} \left(\widehat{\xi}(p) - \xi(p) \right) \quad \text{and} \quad W_n = r_n^{-1} \left(\frac{p - F(p)}{f(p)} \right).$$

The result is established if $V_n - W_n \xrightarrow{\mathbb{P}} 0$ as $n \rightarrow +\infty$. It suffices to prove that V_n and W_n satisfy the conditions of Lemma 1 of Ghosh (1971):

- **condition (a)** : for all $\delta > 0$, there exists $\varepsilon = \varepsilon(\delta)$ such that $\mathbb{P}(|W_n| > \varepsilon) < \delta$.
- **condition (b)** : for all $y \in \mathbb{R}$ and for all $\varepsilon > 0$

$$\lim_{n \rightarrow +\infty} \mathbb{P}(V_n \leq y, W_n \geq k + \varepsilon) \quad \text{and} \quad \lim_{n \rightarrow +\infty} \mathbb{P}(V_n \geq y + \varepsilon, W_n \geq k)$$

condition (a) : from Bienaymé-Tchebyshev's inequality it is sufficient to prove that $\mathbf{E}W_n^2 = \mathcal{O}(1)$. Rewrite $W_n = \frac{r_n^{-1}}{n} \sum_{i=\ell+1}^n h_{\xi(p)}(Y(i))$. Let c_j (for some $j \geq 0$) denote the j -th Hermite coefficient of $h_{\xi(p)}(\cdot)$. Since $h_{\xi(p)}(\cdot)$ has at least Hermite rank $\bar{\tau}_p$, then

$$\begin{aligned} \mathbf{E}W_n^2 &= \frac{r_n^{-2}}{n^2} \sum_{i_1, i_2=1}^n \mathbf{E} \left(h_{\xi(p)}(Y(i_1)) h_{\xi(p)}(Y(i_2)) \right) \\ &= \frac{r_n^{-2}}{n^2} \sum_{i_1, i_2=1}^n \sum_{j_1, j_2 \geq \bar{\tau}_p} c_{j_1} c_{j_2} \mathbf{E} \left(H_{j_1}(Y(i_1)) H_{j_2}(Y(i_2)) \right) \\ &= \frac{r_n^{-2}}{n^2} \sum_{i_1, i_2=1}^n \sum_{j \geq \bar{\tau}_p} \frac{(c_j)^2}{(j)!} \rho(i_2 - i_1)^j \\ &= \mathcal{O} \left(r_n^{-2} \times \frac{1}{n} \sum_{|i| < n} \rho(i)^{\bar{\tau}_p} \right) = \mathcal{O}(1), \end{aligned}$$

from Remark 1.

condition (b) : let $y \in \mathbb{R}$, we have

$$\begin{aligned} \{V_n \leq y\} &= \left\{ \widehat{\xi}(p) \leq y \times r_n + \xi(p) \right\} \\ &= \left\{ p \leq \widehat{F}(y \times r_n + \xi(p)) \right\} = \{Z_n \leq y_n\}, \end{aligned} \tag{11}$$

with

$$Z_n = \frac{r_n^{-1}}{f(\xi(p))} \left(F(y \times r_n + \xi(p)) - \widehat{F} \left(\frac{y}{\sqrt{r_n}} + \xi(p) \right) \right)$$

and

$$y_n = \frac{r_n^{-1}}{f(\xi(p))} \left(F(y \times r_n + \xi(p)) - p \right)$$

Under Assumption $\mathbf{A}(\xi(\mathbf{p}))$, we have $y_n \rightarrow y$, as $n \rightarrow +\infty$. Now, prove that $Z_n - W_n \xrightarrow{\mathbb{P}} 0$. Without loss of generality, assume $y > 0$. Then, we have

$$\begin{aligned} W_n - Z_n &= \frac{r_n^{-1}}{f(p)} \left(\widehat{F}(y \times r_n + \xi(p)) - F(y \times r_n + \xi(p)) - \widehat{F}(\xi(p)) + F(\xi(p)) \right) \\ &= \frac{r_n^{-1}}{n} \frac{1}{f(\xi(p))} \sum_{i=1}^n h_{\xi(p),n}(Y(i)) \end{aligned}$$

where $h_{\xi(p),n}(\cdot)$ is the function defined for $t \in \mathbb{R}$ by :

$$h_{\xi(p),n}(t) = \mathbf{1}_{\left\{ \xi(p) \leq g(t) \leq \xi(p) + y \times r_n \right\}}(t) - \mathbb{P}\left(\xi(p) \leq g(Y) \leq \xi(p) + y \times r_n\right).$$

For n sufficiently large, the function $h_{\xi(p),n}(\cdot)$ has Hermite rank $\bar{\tau}_p$. Denote by $c_{j,n}$ the j -th Hermite coefficient of $h_{\xi(p),n}(\cdot)$. From Lemma 3, there exists a sequence $(\kappa_j)_{j \geq \bar{\tau}_p}$ such that, as $n \rightarrow +\infty$

$$c_{j,n} \sim \kappa_j \times r_n.$$

Since, for all $n \geq 1$ $\mathbf{E}(h_n(Y)^2) = \sum_{j \geq \bar{\tau}_p} (c_{j,n})^2 / j! < +\infty$, it is clear that the sequence $(\kappa_j)_{j \geq \bar{\tau}_p}$ is such that $\sum_{j \geq \bar{\tau}_p} (\kappa_j)^2 / j! < +\infty$. By denoting λ a positive constant, we get, as $n \rightarrow +\infty$

$$\begin{aligned} \mathbf{E}(W_n - Z_n)^2 &= \frac{r_n^{-2}}{n^2} \frac{1}{f(\xi(p))^2} \sum_{i_1, i_2=1}^n \mathbf{E}(h_{\xi(p),n}(Y(i_1)) h_{\xi(p),n}(Y(i_2))) \\ &= \frac{r_n^{-2}}{n^2} \frac{1}{f(\xi(p))^2} \sum_{i_1, i_2=1}^n \sum_{j_1, j_2 \geq \bar{\tau}_p} c_{j_1, n} c_{j_2, n} \mathbf{E}(H_{j_1}(Y(i_1)) H_{j_2}(Y(i_2))) \\ &= \frac{r_n^{-2}}{n^2} \frac{1}{f(\xi(p))^2} \sum_{i_1, i_2=1}^n \sum_{j \geq \bar{\tau}_p} \frac{c_{j, n}^2}{j!} \rho(i_2 - i_1)^j \\ &\leq \lambda \frac{r_n^{-2}}{n} \sum_{j \geq \bar{\tau}_p} \frac{(\kappa_j)^2}{j!} r_n^2 \sum_{|i| < n} \rho(i)^j = \mathcal{O}\left(\frac{1}{n} \sum_{|i| < n} \rho(i)^{\bar{\tau}_p}\right) = \mathcal{O}(r_n^2), \end{aligned}$$

from Remark 1. Therefore, $W_n - Z_n$ converges to 0 in probability, as $n \rightarrow +\infty$. Thus, for all $\varepsilon > 0$, we have, as $n \rightarrow +\infty$,

$$\mathbb{P}(V_n \leq y, W_n \geq y + \varepsilon) = \mathbb{P}(Z_n \leq y_n, W_n \geq y + \varepsilon) \rightarrow 0.$$

Following the sketch of this proof, we also have $\mathbb{P}(V_n \geq y + \varepsilon, W_n \leq y) \rightarrow 0$, ensuring condition (b). Therefore, $W_n - Z_n$ converges to 0 in probability, as $n \rightarrow +\infty$. Thus, for all $\varepsilon > 0$, we have, as $n \rightarrow +\infty$,

$$\mathbb{P}(V_n \leq y, W_n \geq y + \varepsilon) = \mathbb{P}(Z_n \leq y_n, W_n \geq y + \varepsilon) \rightarrow 0.$$

Following the sketch of this proof, we also have $\mathbb{P}(V_n \geq y + \varepsilon, W_n \leq y) \rightarrow 0$, ensuring condition (b).

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