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MATRIX PARAMETER ESTIMATION IN AN AUTOREGRESSION MODEL

The vector difference equation $\xi_k = Af(\xi_{k-1}) + \varepsilon_k$, where (ε_k) is a square integrable difference martingale, is considered. A family of estimators $\check{A}_n$ depending, besides the sample size n, on a bounded Lipschitz function is constructed. Convergence in distribution of $\sqrt{n}\,(\check{A}_n - A)$ as $n \to \infty$ is proved with the use of stochastic calculus. Ergodicity and even stationarity of (ε_k) is not assumed, so the limiting distribution may be, as the example shows, other than normal.

Introducton

We consider the vector autoregression process

$$\xi_k = Af(\xi_{k-1}) + \varepsilon_k, \quad k \in \mathbb{N}. \tag{1}$$

Here, A is an unknown square matrix, f is a prescribed function, and (ε_k) is a square integrable difference martingale with respect to some flow $(\mathcal{F}_k, k \in \mathbb{Z}_+)$ of σ-algebras such that the random variable ξ_0 is $\mathcal{F}_0$-measurable. In the detailed form, the assumption about (ε_k) means that for any k ε_k is $\mathcal{F}_k$-measurable,

$$\mathrm{E}|\varepsilon_k|^2 < \infty \tag{2}$$

and

$$\mathrm{E}(\varepsilon_k|\mathcal{F}_{k-1}) = 0. \tag{3}$$

All vectors are regarded, unless otherwise stated, as columns. Then $a^\top b$ and $ab^\top$ signify scalar and tensor product respectively. The latter is otherwise denoted $a \otimes b$ (this is a $(0,2)$-tensor), in particular $a^{\otimes 2} = aa^\top$. We use the Euclidean norm of vectors, denoting it $|\cdot|$, and the operator norm of matrices. Other notation: $B^\dagger$ – the pseudoinverse to B; O – the null matrix; l.i.p. – limit in probability; $\xrightarrow{\mathrm{d}}$ – the weak convergence of the finite-dimensional distributions of random functions, in particular the convergence in distribution of random vectors.

Let h be a vector function such that for some n

$$\mathrm{E}\left(|\xi_n| + |Af(\xi_n)|\right)|h(\xi_{n-1})| + \mathrm{E}|h(\xi_{n-1})| < \infty.$$

Then from (1) – (3) we have $\mathrm{E}\left(\xi_n - Af(\xi_{n-1})\right) \otimes h(\xi_{n-1}) = \mathrm{O}$, whence

$$A = \left(\mathrm{E}\xi_n \otimes h(\xi_{n-1})\right)\left(\mathrm{E}f(\xi_{n-1}) \otimes h(\xi_{n-1})\right)^{-1}$$

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provided the inverse exists. This prompts the estimator

$$\check{A}_n = \left(\sum_{k=1}^{n} \xi_k \otimes h(\xi_{k-1})\right) \left(\sum_{k=1}^{n} f(\xi_{k-1}) \otimes h(\xi_{k-1})\right)^{\dagger} \tag{4}$$

coinciding in the case $f(x) = x$ with the LSE.

The goal of the article is to study the asymptotic behaviour of the normalized deviation $\sqrt{n}\left(\check{A}_n - A\right)$ as $n \to \infty$. The use of stochastic calculus underlying our approach allows us to dispense with the assumptions of ergodicity and even asymptotic stationarity of the sequence (ε_k), thereat the limiting distribution of the studied statistic may be other than normal. This is the main distinction of our results from A.Ya. Dorogovtsev's ones [1] essentially based on the ergodicity assumption.

Preliminaries

Let E^0 denote $\mathrm{E}(\cdots|\mathcal{F}_0)$.

Lemma 1. *Let conditions (2) and (3) be fulfilled and there exist a number q such that for all x*

$$|Af(x)| \le q|x|. \tag{5}$$

Then, for any k,

$$\mathrm{E}^0|\xi_k|^2 \le q^{2k}|\xi_0|^2 + \sum_{i=0}^{k-1} q^i \mathrm{E}^0|\varepsilon_{k-i}|^2.$$

Proof. Writing, on the basis of (1),

$$|\xi_k|^2 = |Af(\xi_{k-1})|^2 + 2Af(\xi_{k-1})^{\top}\varepsilon_k + |\varepsilon_k|^2 \tag{6}$$

we deduce our assertion from (2), (3) and (5) by induction.

Denote further $\sigma_k^2 = \mathrm{E}\left(\varepsilon_k^{\otimes 2}|\mathcal{F}_{k-1}\right)$, $\chi_k^N = I\{|\xi_k| > N\}$, $I_k^N = I\{|\varepsilon_k| > (1-q)N\}$, $b_k^N = \mathrm{E}^0|\xi_k|^2\chi_k^N$. Obviously,

$$\mathrm{E}\left(|\varepsilon_k|^2|\mathcal{F}_{k-1}\right) = \mathrm{tr}\sigma_k^2. \tag{7}$$

Lemma 2. *Let conditions (2), (3) and (5) be fulfilled and*

$$q < 1. \tag{8}$$

Then for any k

$$b_k^N \le q^2 b_{k-1}^N + \mathrm{E}^0|\varepsilon_k|^2\chi_{k-1}^N + 2(q/(1-q))^2 N^{-2}\mathrm{E}^0|\xi_{k-1}|^2\mathrm{tr}\sigma_k^2 + 2\mathrm{E}^0|\varepsilon_k|^2 I_k^N.$$

Proof. Due to (1) and (5),

$$\chi_k^N \le \chi_{k-1}^N + I_k^N,$$

which together with (6), (5) and the obvious inequality $|a^{\top}b| \le |a|^2 + |b|^2$ yields

$$|\xi_k|^2\chi_k^N \le q^2|\xi_{k-1}|^2\chi_{k-1}^N + 2Af(\xi_{k-1})^{\top}\varepsilon_k\chi_{k-1}^N + |\varepsilon_k|^2\chi_{k-1}^N + 2(q^2|\xi_{k-1}|^2 + |\varepsilon_k|^2)I_k^N.$$

By Lemma 1 and condition (5), $\mathrm{E}^0|Af(\xi_{k-1})|^2 < \infty$. Hence, because of (2) and (3), $\mathrm{E}^0\left(Af(\xi_{k-1})^{\top}\varepsilon_k|\mathcal{F}_{k-1}\right) = 0$. The equality

$$\mathrm{E}^0|\xi_{k-1}|^2 I_k^N = \mathrm{E}^0\left(|\xi_{k-1}|^2\mathrm{P}\{|\varepsilon_k| > (1-q)N|\mathcal{F}_{k-1}\}\right),$$

together with condition (8), Chebyshev's inequality, and equality (7) completes the proof.

In what follows, C is a generic constant.

Obviously, $\mathrm{E}^0\chi_i^N \le N^{-2}b_i^N$. Hence and from the previous lemmas we deduce (the details can be found in the proof of Theorem 2 [2])

Corollary 1. *Let conditions (2), (3), (5), and (8) be fulfilled,*

$$\lim_{N\to\infty}\varlimsup_{n\to\infty}\frac{1}{n}\sum_{k=1}^{n}\mathrm{E}|\varepsilon_k|^2 I\{|\varepsilon_k|>N\}=0, \tag{9}$$

and let there exist an $\mathcal{F}_0$*-measurable random variable* υ *such that for all* k

$$\mathrm{E}\left(|\varepsilon_k|^2|\mathcal{F}_{k-1}\right)\le\upsilon. \tag{10}$$

Then with probability 1

$$\lim_{N\to\infty}\varlimsup_{n\to\infty}\frac{1}{n}\sum_{k=1}^{n}b_k^N=0.$$

The main results

Let h be a Borel function such that

$$|h(x)|\le C|x|. \tag{11}$$

Denote $\eta_k=h(\xi_k)$, $K_n=\frac{1}{\sqrt{n}}\sum_{k=1}^n\varepsilon_k\otimes\eta_{k-1}$, $Q_n=\frac{1}{n}\sum_{k=0}^{n-1}f(\xi_k)\otimes\eta_k$, $T_n=\sqrt{n}(AQ_nQ_n^\dagger-A)$, $G_n=\frac{1}{n}\sum_{k=1}^n\sigma_k^2\otimes\eta_{k-1}^{\otimes 2}$,

$$Y_n(t)=\frac{1}{\sqrt{n}}\sum_{k=1}^{[nt]}\varepsilon_k\otimes\eta_{k-1}. \tag{12}$$

Then, because of (4),

$$\sqrt{n}(\check{A}_n-A)=K_nQ_n^\dagger+T_n. \tag{13}$$

By construction and conditions (2), (3) and (5), Y_n is a locally square integrable martingale with quadratic characteristic

$$\langle Y_n\rangle(t)=n^{-1}[nt]G_{[nt]}^*, \tag{14}$$

where $*$ is a linear operation in the space of 4-valent tensors such that

$$(a\otimes b\otimes c\otimes d)^*=a\otimes c\otimes b\otimes d.$$

Theorem 1. *Let conditions (2), (3), (5) and (8) – (11) be fulfilled, and let there exist a random* $(0,4)$*-tensor* G *such that*

$$G_n\xrightarrow{\mathrm{d}}G. \tag{15}$$

Then $Y_n\xrightarrow{\mathrm{d}}Y$*, where* Y *is a continuous local martingale with quadratic characteristic* $\langle Y\rangle(t)=G^*t$*.*

Proof. According to Corollary in [3] and in view of (14) and (15), it suffices to show that for any t

$$\mathrm{E}\sup_{s\le t}\|Y_n(s)-Y_n(s-)\|^2\to 0. \tag{16}$$

The argument in [3] doess not change if the expectation is taken conditioned on $\mathcal{F}_0$, so in (16) E and $\to$ may be substituted by E^0 and $\xrightarrow{\mathrm{P}}$, respectively. This weakened version of (16) is equivalent, because of (12), to the following relation:

$$n^{-1}\mathrm{E}^0\max_{k\le nt}\rho_k\xrightarrow{\mathrm{P}}0,$$

where $\rho_k = |\varepsilon_k|^2 |\eta_{k-1}|^2$. Since for any $\delta > 0$

$$\max_k \rho_k \le \delta n + \sum_k \rho_k I\{\rho_k > \delta n\},$$

it remains to prove that the random variables $\sqrt{\rho_k/n}$ satisfy the Lindeberg condition: for any $\delta > 0$

$$\frac{1}{n} \sum_{k \le nt} \mathrm{E}^0 \rho_k I\{\rho_k > \delta n\} \xrightarrow{\mathrm{P}} 0. \tag{17}$$

Writing on the basis of (11)

$$\rho_k I\{\rho_k > \delta n\} \left(I\{|\xi_{k-1}| \le N\} + I\{|\xi_{k-1}| > N\} \right)$$
$$\le C^2 \left(N^2 |\varepsilon_k|^2 I\{|\varepsilon_k|^2 > (CN)^{-2} \delta n\} + |\varepsilon_k|^2 |\xi_{k-1}|^2 \chi_{k-1}^N \right),$$

we deduce (17) from both the conditions and the conclusion of Corollary 1.

Applying Theorem 1 to the compound processes (Y_n, Q_n) where the second component does not depend on t, we obtain

Corollary 2. *Let conditions (2), (3), (5), and (8) – (11) be fulfilled, and let there exist given on a common probability space random* $(0,4)$*-tensor* G *and* $(0,2)$*-tensor* Q *such that*

$$(G_n, Q_n) \xrightarrow{\mathrm{d}} (G, Q). \tag{18}$$

Then $(Y_n, Q_n) \xrightarrow{\mathrm{d}} (Y, Q)$*, where* Y *is a continuous local martingale w. r. t. some flow* $(\mathcal{F}(t), t \in \mathbb{R}_+)$ *such that* $\langle Y \rangle(t) = G^* t$ *and the tensor-valued r. v.* Q *is* $\mathcal{F}(0)$*-measurable.*

Theorem 2. *Let the conditions of Corollary 2 be fulfilled and* $\det Q \ne 0$ *a. s. Then*

$$\sqrt{n}(\check{A}_n - A) \xrightarrow{\mathrm{d}} Y(1) Q^{-1}. \tag{19}$$

Proof. By Corollary 2,

$$(Y_n(1), Q_n) \xrightarrow{\mathrm{d}} (Y(1), Q).$$

But $Y_n(1) = K_n$, which together with the nondegeneracy of Q implies that $K_n Q_n^\dagger \xrightarrow{\mathrm{d}} K Q^{-1}$. Now, to obtain the assertion of the theorem from (13), it remains to note that

$$\mathrm{P}\{T_n \ne \mathrm{O}\} \le \mathrm{P}\{\det Q_n \ne \mathrm{O}\} \to 0.$$

Simpler versions of condition (18)

Denote $f_0(x) = x$ and, for $r \ge 1$,

$$f_r(x_0, \dots, x_r) = A f(f_{r-1}(x_0, \dots, x_{r-1})) + x_r. \tag{20}$$

Then

$$\xi_k = f_r(\xi_{k-r}, \varepsilon_{k-r+1}, \dots, \varepsilon_k), \quad r < k, \tag{21}$$

and

$$|f_r(x_0, \dots, x_r)| \le \sum_{i=0}^r q^i |x_{r-i}|. \tag{22}$$

Below X_r stands for $(x_1, \dots, x_r)$, and d is the dimensionality of each x_j.

Lemma 3. *Let for all x, y*

$$|Af(x) - Af(y)| \le q|x-y|. \tag{23}$$

Then for all x, y, r, X_r

$$|f_r(x, X_r) - f_r(y, X_r)| \le q^r|x-y|.$$

Proof. Due to (20) and (23),

$$|f_r(x, X_r) - f_r(y, X_r)| \le q|f_{r-1}(x, X_{r-1}) - f_{r-1}(y, X_{r-1})|,$$

so it remains to apply the induction.

Corollary 3. *Under the conditions of Lemma 3, for any N*

$$\lim_{r\to\infty} \sup_{|x|\le N, X_r\in\mathbb{R}^{rd}} |f_r(x, X_r) - f_r(0, X_r)| = 0.$$

Corollary 4. *Let conditions (5), (8), (11) and (23) be fulfilled and for any x, y*

$$|h(x) - h(y)| \le C|x-y|. \tag{24}$$

Then for any $N > 0$

$$\lim_{r\to\infty} \sup_{|x|\le N, X_r\in\mathbb{R}^{rd}} \|f(f_r(x, X_r)) \otimes h(f_r(x, X_r)) - f(f_r(0, X_r)) \otimes h(f_r(0, X_r))\| = 0, \tag{25}$$

$$\lim_{r\to\infty} \sup_{|x|\le N, X_r\in\mathbb{R}^{rd}} \|h(f_r(x, X_r))^{\otimes 2} - h(f_r(0, X_r))^{\otimes 2}\| = 0. \tag{26}$$

Denote further $\xi_k^r = f_r(0, \varepsilon_{k-r+1}, \dots, \varepsilon_k)$, $\eta_k^r = h(\xi_k^r)$, $Q_n^r = \frac{1}{n}\sum_{k=r}^{n-1} f(\xi_k^r) \otimes \eta_k^r$, $G_n^r = \frac{1}{n}\sum_{k=r}^{n} \sigma_k^2 \otimes (\eta_{k-1}^r)^{\otimes 2}$. We endow the space of $(0,4)$-tensors with such a norm that for any $(0,2)$-tensors A_1 and A_2, $\|A_1 \otimes A_2\| = \|A_1\|\|A_2\|$.

Lemma 4. *Let conditions (2), (3), (5), (8) – (11), (23) and (24) be fulfilled and*

$$|f(x)| \le C|x|. \tag{27}$$

Then almost surely

$$\lim_{r\to\infty} \overline{\lim_{n\to\infty}} \mathrm{E}^0\|Q_n - Q_n^r\| = 0, \tag{28}$$

$$\lim_{r\to\infty} \overline{\lim_{n\to\infty}} \mathrm{E}^0\|G_n - G_n^r\| = 0. \tag{29}$$

Proof. By Corollary 4 for any $N > 0$,

$$\lim_{r\to\infty} \overline{\lim_{n\to\infty}} \frac{1}{n}\sum_{k=r}^{n-1} \mathrm{E}\|f(\xi_k) \otimes \eta_k - f(\xi_k^r) \otimes \eta_k^r\| I\{|\xi_k| \le N\} = 0. \tag{30}$$

Due to (11) and (27),

$$\mathrm{E}^0\|f(\xi_k) \otimes \eta_k\|\chi_k^N \le C^2 b_k^N,$$

so, by Corollary 1,

$$\lim_{N\to\infty} \overline{\lim_{n\to\infty}} \frac{1}{n}\sum_{k=0}^{n-1} \mathrm{E}^0\|f(\xi_k) \otimes \eta_k\|\chi_k^N = 0. \tag{31}$$

Further, for $k \ge r$

$$\mathrm{E}^0\|f(\xi_k^r) \otimes \eta_k^r\| = \mathrm{E}^0|f(f_r(0, \varepsilon_{k-r+1}, \dots, \varepsilon_k))||h(f_r(0, \varepsilon_{k-r+1}, \dots, \varepsilon_k))|,$$

whence, in view of (22), (27), and (11),

$$\mathrm{E}\|f(\xi_k^r)\otimes\eta_k^r\|\chi_k^N \le C^2\mathrm{E}\left(\sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|\right)^2 \chi_k^N. \tag{32}$$

Writing the Cauchy–Buniakowsky inequality

$$\left(\sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|\right)^2 \le \sum_{j=0}^{r-1} q^j \sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|^2,$$

we get for an arbitrary $L > 0$

$$\begin{aligned}\mathrm{E}&\left(\sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|\right)^2 \chi_k^N \\ &\le (1-q)^{-1}\left(\mathrm{E}\sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|^2 I\{|\varepsilon_{k-i}|>L\} + L^2\mathrm{P}\{|\xi_k|>N\}\sum_{i=0}^{r-1} q^i\right).\end{aligned} \tag{33}$$

Lemma 1 together with (8) and (10) implies that

$$\lim_{N\to\infty}\overline{\lim_{n\to\infty}}\frac{1}{n}\sum_{k=0}^{n}\mathrm{P}\{|\xi_k|>N\} = 0. \tag{34}$$

Obviously, for arbitrary nonnegative numbers $u_0, \dots, u_{r-1}, v_1, \dots, v_{n-1}$,

$$\sum_{k=r}^{n-1}\sum_{i=0}^{r-1} u_i v_{k-i} \le \sum_{i=0}^{r-1} u_i \sum_{j=1}^{n-1} v_j,$$

so conditions (8) and (9) imply that

$$\lim_{L\to\infty}\sup_r \overline{\lim_{n\to\infty}}\frac{1}{n}\sum_{k=r}^{n-1}\mathrm{E}\sum_{i=0}^{r-1} q^i|\varepsilon_{k-i}|^2 I\{|\varepsilon_{k-i}|>L\} = 0,$$

whence, in view of (32) – (34),

$$\lim_{N\to\infty}\sup_r \overline{\lim_{n\to\infty}}\frac{1}{n}\sum_{k=r}^{n-1}\mathrm{E}\|f(\xi_k^r)\otimes\eta_k^r\|\chi_k^N = 0.$$

Combining this with (30) and (31), we arrive at (28).

The proof of (29) is similar.

Corollary 5. *Let the conditions of Lemma 4 be fulfilled and for any $r \in \mathbb{N}$ there exist a pair (Q^r, G^r) of tensors such that*

$$(Q_n^r, G_n^r) \xrightarrow{\mathrm{d}} (Q^r, G^r) \quad \text{as} \quad n \to \infty.$$

Then the sequence $((Q^r, G^r), r \in \mathbb{N})$ converges in distribution to some limit (Q, G) and relation (18) holds.

Lemma 5. *Let the sequence (ε_k) satisfy conditions (9) and (10) and for any uniformly bounded sequence (α_k) of Borel functions on $\mathbb{R}^{rd}$*

$$\frac{1}{n}\sum_{k=r}^{n-1}\big(\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k)-\mathrm{E}^0\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k)\big)\xrightarrow{\mathrm{P}}\mathrm{O}. \tag{36}$$

Then this relation holds for any sequence (α_k) of Borel functions such that

$$|\alpha_k(x_1,\dots,x_r)|\le C\left(\sum_{i=1}^{r}|x_i|^2+1\right). \tag{37}$$

Proof. Denote $\zeta_k=\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k)$. Then for any $N>0$

$$\frac{1}{n}\sum_{k=r}^{n-1}\big(\zeta_k I\{|\varepsilon_{k-r+1}|\le N,\dots,|\varepsilon_k|\le N\}-\mathrm{E}^0\zeta_k I\{|\varepsilon_{k-r+1}|\le N,\dots,|\varepsilon_k|\le N\}\big)\xrightarrow{\mathrm{P}}0,$$

so it suffices to prove that, for $j=0,\dots,r-1$,

$$\lim_{N\to\infty}\overline{\lim_{n\to\infty}}\frac{1}{n}\sum_{k=1}^{n}\mathrm{E}^0|\zeta_k|I\{|\varepsilon_{k-j}|>N\}=0\quad\text{a.s.} \tag{38}$$

By assumption,

$$\mathrm{E}^0|\zeta_k|I\{|\varepsilon_{k-j}|>N\}\le C\left(\mathrm{P}\{|\varepsilon_{k-j}|>N|\mathcal{F}_0\}+\sum_{i=0}^{k-1}\mathrm{E}^0|\varepsilon_{k-i}|^2 I\{|\varepsilon_{k-j}|>N\}\right). \tag{39}$$

Due to (10), $\mathrm{P}\{|\varepsilon_i|>N|\mathcal{F}_0\}\le \upsilon^2N^{-2}$ and $\mathrm{E}^0|\varepsilon_{k-i}|^2I\{|\varepsilon_{k-j}|>N\}\le \upsilon^4N^{-2}$ as $i\ne j$, which together with (39) and (9) implies (38).

Remark. Obviously, if relation (36) holds for any sequence of $\mathbb{R}$-valued functions (uniformly bounded or satisfying (37)), then for any $m\in\mathbb{N}$ it is valid for any sequence of $\mathbb{R}^m$-valued functions with the same property.

The proof of the following statement is similar.

Lemma 6. *Let the sequence (ε_k) satisfy conditions (9) and (10) and for any uniformly bounded sequence (α_k) of $\mathbb{R}$-valued Borel functions on $\mathbb{R}^{rd}$*

$$\frac{1}{n}\sum_{k=r}^{n-1}\big(\sigma_k^2\otimes\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k)-\mathrm{E}^0(\sigma_k^2\otimes\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k))\big)\xrightarrow{\mathrm{P}}\mathrm{O} \tag{40}$$

(here $\otimes$ signifies the multiplication of a tensor by a real number). Then this relation holds for any sequence (α_k) of tensor-valued functions satisfying (37) (with $\|\cdot\|$ instead of $|\cdot|$ on the left-hand side).

Corollary 6. *Let the conditions of Lemmas 4 and 5 be fulfilled and for any uniformly bounded sequence (α_k) of $\mathbb{R}$-valued Borel functions on $\mathbb{R}^{rd}$ the sequence*

$$\left(\frac{1}{n}\sum_{k=r}^{n-1}\mathrm{E}^0\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k),\quad n=r,r+1,\dots\right)$$

converge in probability. Then the sequence $(Q_n^r,\quad n=r,r+1\dots)$ converges in probability.

Corollary 7. *Let the conditions of Lemmas 4 and 6 be fulfilled and for any uniformly bounded sequence of* $\mathbb{R}$*-valued functions the sequence*

$$\left(\frac{1}{n}\sum_{k=r}^{n-1} \mathrm{E}^0\sigma_k^2\alpha_k(\varepsilon_{k-r+1},\dots,\varepsilon_k), \quad n=r,r+1,\dots\right)$$

converge in probability. Then the sequence $(G_n^r, \quad n=r,r+1\dots)$ *converges in probability.*

An example

Suppose that conditions (5), (8), (11), (23) and (24) are fulfilled. Let also $\varepsilon_k = \gamma_k\chi_k$, where (γ_k) and (χ_k) are independent sequences of random variables and i.i.d. random vectors, respectively, $|\gamma_k| \le C$, and let for any $r \in \mathbb{N}$ and bounded Borel function g the sequence

$$\left(\frac{1}{n}\sum_{k=r}^{n-1} g(\gamma_{k-r+1},\dots,\gamma_k), \quad n=r,r+1,\dots\right)$$

converge in probability; $\mathrm{E}\chi_1 = 0$, $\mathrm{E}\chi_1^{\otimes 2} = \mathrm{I}$.

For $\mathcal{F}_k$, we take the σ-algebra generated by $\xi_0;\chi_1,\dots,\chi_k;\gamma_1,\gamma_2,\dots$ (so that the whole sequence (γ_k) is $\mathcal{F}_0$-measurable). Then $\sigma_k^2 = \gamma_k^2\mathrm{I}$,

$$G_n^r = \mathrm{I}\otimes\frac{1}{n}\sum_{k=r}^{n}(\gamma_k\eta_k^r)^{\otimes 2} \tag{41}$$

and conditions (2), (3), and (10) are fulfilled. So is (9), because the γ_k's are uniformly bounded and χ_k's are identically distributed.

To deduce (19) from Theorem 2 and Corollary 5 it suffices to verify the conditions of Corollaries 6 and 7. In view of (41) and the expressions for Q_n^r and η_k^r, we may confine ourselves with the case $\alpha_k = \alpha$.

By the Stone – Weierstrass theorem, α can be approximated uniformly on compacta with finite linear combinations of functions of the kind $h(y)h_1(x_1)\dots h_r(x_r)$ $(y\in\mathbb{R}^r, x_j \in \mathbb{R}^d)$. By the choice of $\mathcal{F}_k$ and the assumptions on (γ_k) and (χ_k),

$$\mathrm{E}^0 h(\overline{\gamma}_k)h_1(\chi_{k-r+1})\dots h_r(\chi_k) = h(\overline{\gamma}_k)\prod_{i=1}^{r}\mathrm{E}h_i(\chi_1),$$

where $\overline{\gamma}_k = (\gamma_{k-r+1},\dots,\gamma_k)$.

Hence and from the Chebyshev's inequality, (36) emerges. The last condition of Corollary 6 follows from (41) and the above assumption on (γ_k).

If $\det Q \ne 0$, then Theorem 2 asserts (19). If herein $\text{l.i.p.}_{n\to\infty}\frac{1}{n}\sum_{k=r}^{n} g(\overline{\gamma}_k)$ is random, then the limiting distribution will not be Gaussian.

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