Supplement to "Optimal sup-norm rates and uniform inference on nonlinear functionals of nonparametric IV regression"

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This supplementary appendix contains material to support our paper. Appendix D presents pointwise normality of sieve t-statistics for nonlinear functionals of NPIV under low-level sufficient conditions. Appendix E contains background material on B-spline and wavelet bases and the equivalence between Besov and wavelet sequence norms. Appendix F contains material on useful matrix inequalities and convergence results for random matrices. The secondary supplementary appendix contains additional technical lemmas and all of the proofs (Appendix G).

Appendix D: Pointwise asymptotic normality of sieve t-statistics

In this section we derive the pointwise asymptotic normality of sieve t-statistics for nonlinear functionals of a NPIV function under low-level sufficient conditions. Previously, under some high-level conditions, Chen and Pouzo (2015) established the pointwise asymptotic normality of sieve t-statistics for (possibly) nonlinear functionals of h_0 satisfying general semi/nonparametric conditional moment restrictions including NPIV and nonparametric quantile IV models as special cases. As the sieve NPIV estimator $\widehat{h}$ has a closed-form expression and for the sake of easy reference, we derive the limit theory directly rather than appealing to the general theory in Chen and Pouzo (2015). Our low-level sufficient conditions are tailored to the case in which the functional $f(\cdot)$ is *irregular* in h_0 (i.e., slower than root-n estimable), so that they are directly comparable to the sufficient conditions for the uniform inference theory in Section 4.

We consider a functional $f : \mathcal{H} \subset L^\infty(X) \to \mathbb{R}$ for which $Df(h)[v] = \lim_{\delta\to 0^+}[\delta^{-1} \times \{f(h+\delta v) - f(h)\}]$ exists for all $v \in \mathcal{H} - \{h_0\}$ for all h in a small neighborhood of h_0. Recall that the sieve 2SLS Riesz representer of $Df(h_0)$ is

$$v_n(f)(x) = \psi^J(x)'\big[S'G_b^{-1}S\big]^{-1} Df(h_0)\big[\psi^J\big],$$

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and let

$$\big[s_n(f)\big]^2 = \|\Pi_K T v_n(f)\|^2_{L^2(W)} = \big(Df(h_0)[\psi^J]\big)'\big[S'G_b^{-1}S\big]^{-1}Df(h_0)\big[\psi^J\big]$$

denote its weak norm. Chen and Pouzo (2015) called the functional $f(\cdot)$ an irregular (i.e., slower than $\sqrt{n}$-estimable) functional of h_0 if $s_n(f) \nearrow \infty$ and a regular (i.e., $\sqrt{n}$-estimable) functional of h_0 if $\lim_n s_n(f) < \infty$. Denote

$$\widehat{v}_n(f)(x) = \psi^J(x)'\big[S'G_b^{-1}S\big]^{-1}Df(\widehat{h})\big[\psi^J\big].$$

It is clear that $v_n(f) = \widehat{v}_n(f)$ whenever $f(\cdot)$ is linear.

Recall that $\Omega = E[u_i^2 b^K(W_i)b^K(W_i)']$, that the 2SLS covariance matrix for $\widehat{c}$ (given in equation (2)) is

$$\mho = [S'G_b^{-1}S]^{-1}S'G_b^{-1}\Omega G_b^{-1}S[S'G_b^{-1}S]^{-1},$$

and that the sieve variance for $f(\widehat{h})$ is

$$\big[\sigma_n(f)\big]^2 = \big(Df(h_0)\big[\psi^J\big]\big)'\mho\big(Df(h_0)\big[\psi^J\big]\big).$$

Under Assumption 2(i) and (iii) we have that $[\sigma_n(f)]^2 \asymp [s_n(f)]^2$. Therefore, $f()$ is an irregular functional of h_0 if and only if $\sigma_n(f) \nearrow +\infty$ as $n \to \infty$. Recall that the sieve variance estimator is

$$\big[\widehat{\sigma}(f)\big]^2 = \big(Df(\widehat{h})\big[\psi^J\big]\big)'\widehat{\mho}\big(Df(\widehat{h})\big[\psi^J\big]\big),$$

where $\widehat{\mho}$ is defined in equation (6).

Assumption 2 (continued). (iv′) *We have* $\sup_w E[u_i^2\{|u_i| > \ell(n)\}|W_i = w] = o(1)$ *for any positive sequence with* $\ell(n) \nearrow \infty$.

Assumption 2(iv′) is a mild condition that is trivially satisfied if $E[|u_i|^{2+\epsilon}|W_i = w]$ is uniformly bounded for some $\epsilon > 0$.

Assumption 5′. *Let* η_n *and* η_n' *be sequences of nonnegative numbers such that* $\eta_n = o(1)$ *and* $\eta_n' = o(1)$. *Let* $\sigma_n(f) \nearrow +\infty$ *as* $n \to \infty$. *Either* (a) *or* (b) *of the following options holds*:

(a) *The functional* f is a linear functional and $\sqrt{n}(\sigma_n(f))^{-1}|f(\widetilde{h}) - f(h_0)| = O_p(\eta_n)$.

(b) (i) *The functional* $v \mapsto Df(h_0)[v]$ *is a linear functional*; (ii)

$$\left|\sqrt{n}\frac{f(\widehat{h}) - f(h_0)}{\sigma_n(f)} - \sqrt{n}\frac{Df(h_0)[\widehat{h} - \widetilde{h}]}{\sigma_n(f)}\right| = O_p(\eta_n);$$

(iii) $\frac{\|\Pi_K T(\widehat{v}_n(f) - v_n(f))\|_{L^2(W)}}{\sigma_n(f)} = O_p(\eta_n')$.

Assumption 5′(a) and 5′(b)(i) and (ii) is similar to Assumption 3.5 of Chen and Pouzo (2015). Assumption 5′(b)(iii) controls any additional error arising in the estimation of $\sigma_n(f)$ due to nonlinearity of $f(\cdot)$ and is automatically satisfied when $f(\cdot)$ is a linear functional.

REMARK D.1. Remark 4.1 presents sufficient conditions for Assumption 5′ as a special case, with $f_t = f$, $\underline{\sigma}_n = \sigma_n(f)$, and $\mathcal{T}$ a singleton.

Again these sufficient conditions are formulated to take advantage of the sup-norm rate results in Section 3. Denote

$$\widehat{\mathbb{Z}}_n \equiv \frac{\big(Df(h_0)[\psi^J]\big)'\big[S'G_b^{-1}S\big]^{-1}S'G_b^{-1}}{\sigma_n(f)} \frac{1}{\sqrt{n}} \sum_{i=1}^n b^K(W_i)u_i$$

and $\delta_{V,n} \equiv [\zeta_{b,K}^{(2+\delta)/\delta}\sqrt{(\log K)/n}]^{\delta/(1+\delta)} + \tau_J\zeta\sqrt{(\log J)/n} + \delta_{h,n}$, where $\delta_{h,n} = o_p(1)$ is a positive finite sequence such that $\|\widehat{h} - h_0\|_\infty = O_p(\delta_{h,n})$.

THEOREM D.1. (i) *Let Assumptions* 1(iii), 2(i), (iii), *and* (iv′), 4(i), *and either* 5′(a) *or* 5′(b)(i) *and* (ii) *hold, and let* $\tau_J\zeta\sqrt{(J\log J)/n} = o(1)$. *Then*

$$\sqrt{n}\frac{\big(f(\widehat{h}) - f(h_0)\big)}{\sigma_n(f)} = \widehat{\mathbb{Z}}_n + o_p(1) \to_d N(0,1).$$

(ii) *If* $\|\widehat{h} - h_0\|_\infty = o_p(1)$ *and Assumptions* 2(ii) *and* 3(iii) *hold* (*and* 5′(b)(iii) *also holds if* f *is nonlinear*), *then*

$$\left|\frac{\widehat{\sigma}(f)}{\sigma_n(f)} - 1\right| = O_p\big(\delta_{V,n} + \eta_n'\big) = o_p(1)$$

and

$$\sqrt{n}\frac{\big(f(\widehat{h}) - f(h_0)\big)}{\widehat{\sigma}(f)} = \widehat{\mathbb{Z}}_n + o_p(1) \to_d N(0,1).$$

By exploiting the closed-form expression of the sieve NPIV estimator and by applying exponential inequalities for random matrices, Theorem D.1 derives the pointwise limit theory under lower-level sufficient conditions than those in Chen and Pouzo (2015) for irregular nonlinear functionals. In particular, when specialized to the exogenous case of $X_i = W_i$, $h_0(x) = E[Y_i|W_i = x]$, $K = J$, and $b^K = \psi^J$ with $\tau_J = 1$, the regularity conditions for Theorem D.1 become about the same mild conditions for Theorem 3.2 in Chen and Christensen (2015) on asymptotic normality of sieve t-statistics for nonlinear functionals of series LS estimators. It is now obvious that one could also derive the asymptotic normality of sieve t-statistics for regular (i.e., root-n estimable) nonlinear functionals of a NPIV function under lower-level sufficient conditions by using our sup-norm rates results to verify Assumption 3.5(ii) and Remark 3.1 in Chen and Pouzo (2015).

APPENDIX E: SPLINE AND WAVELET BASES

In this section, we bound the terms $\xi_{\psi,J}$, $e_J = \lambda_{\min}(G_{\psi,J})$, and $\kappa_\psi(J)$ for B-spline and CDV wavelet bases. Although we state the results for the space Ψ_J, they may equally be applied to B_K when B_K is constructed using B-spline or CDV wavelet bases.

E.1 *Spline bases*

We construct a univariate B-spline basis of order $r \geq 1$ (or degree $r-1 \geq 0$) with $m \geq 0$ interior knots and support $[0,1]$ in the following way. Let $0 = t_{-(r-1)} = \cdots = t_0 < t_1 < \cdots < t_m < t_{m+1} = \cdots = t_{m+r} = 1$ denote the extended knot sequence and let $I_0 = [t_0, t_1), \ldots, I_m = [t_m, t_{m+1}]$. A basis of order 1 is constructed by setting

$$N_{j,1}(x) = \begin{cases} 1, & \text{if } x \in I_j, \\ 0, & \text{otherwise} \end{cases}$$

for $j = 0, \ldots m$. Bases of order $r > 1$ are generated recursively according to

$$N_{j,r}(x) = \frac{x - t_j}{t_{j+r-1} - t_j} N_{j,r-1}(x) + \frac{t_{j+r} - x}{t_{j+r} - t_{j+1}} N_{j+1,r-1}(x)$$

for $j = -(r-1), \ldots, m$, where we adopt the convention $\frac{1}{0} := 0$ (see Section 5 of DeVore and Lorentz (1993)). This results in a total of $m + r$ splines of order r, namely $N_{-(r-1),r}, \ldots, N_{m,r}$. Each spline is a polynomial of degree $r-1$ on each interior interval $I_1, \ldots, I_m$ and is $(r-2)$-times continuously differentiable on $[0,1]$ whenever $r \geq 2$. The mesh ratio is defined as

$$\operatorname{mesh}(m) = \frac{\max\limits_{0 \leq j \leq m} (t_{j+1} - t_j)}{\min\limits_{0 \leq j \leq m} (t_{j+1} - t_j)}.$$

Clearly $\operatorname{mesh}(m) = 1$ whenever the knots are placed evenly (i.e., $t_i = \frac{i}{m+1}$ for $i = 1, \ldots, m$ and $m \geq 1$), and we say that the mesh ratio is *uniformly bounded* if $\operatorname{mesh}(m) \lesssim 1$ as $m \to \infty$. Each $N_{j,r}$ has continuous derivatives of orders $\leq r-2$ on $(0,1)$. We let the space $\operatorname{BSpl}(r, m, [0,1])$ be the closed linear span of the $m+r$ splines $N_{-(r-1),r}, \ldots, N_{m,r}$.

We construct B-spline bases for $[0,1]^d$ by taking tensor products of univariate bases. First generate d univariate bases $N_{-(r-1),r,i}, \ldots, N_{m,r,i}$ for each of the d components x_i of x as described above. Then form the vector of basis functions ψ^J by taking the tensor product of the vectors of univariate basis functions, namely,

$$\psi^J(x_1, \ldots, x_d) = \bigotimes_{i=1}^{d} \begin{pmatrix} N_{-(r-1),r,i}(x_i) \\ \vdots \\ N_{m,r,i}(x_i) \end{pmatrix}.$$

The resulting vector ψ^J has dimension $J = (r+m)^d$. Let $\psi_{J1}, \ldots, \psi_{JJ}$ denote its J elements.

Stability properties The following two lemmas bound $\xi_{\psi,J}$, and the minimum eigenvalue and condition number of $G_\psi = G_{\psi,J} = E[\psi^J(X_i)\psi^J(X_i)']$ when $\psi_{J1}, \ldots, \psi_{JJ}$ is constructed using univariate and tensor products of B-spline bases with uniformly bounded mesh ratio.

LEMMA E.1. *Let X have support* $[0,1]$ *and let $\psi_{J1} = N_{-(r-1),r}, \ldots, \psi_{JJ} = N_{m,r}$ be a univariate B-spline basis of order $r \geq 1$ with $m = J - r \geq 0$ interior knots and uniformly bounded mesh ratio. Then* (a) *$\xi_{\psi,J} = 1$ for all $J \geq r$;* (b) *if the density of X is uniformly* *bounded away from* 0 *and* ∞ *on* $[0,1]$, *then there exist finite positive constants* c_ψ *and* C_ψ *such that* $c_\psi J \le \lambda_{\max}(G_\psi)^{-1} \le \lambda_{\min}(G_\psi)^{-1} \le C_\psi J$ *for all* $J \ge r$; (c) $\lambda_{\max}(G_\psi)/\lambda_{\min}(G_\psi) \le C_\psi/c_\psi$ *for all* $J \ge r$.

LEMMA E.2. *Let* X *have support* $[0,1]^d$ *and let* $\psi_{J1}, \dots, \psi_{JJ}$ *be a B-spline basis formed as the tensor product of* d *univariate bases of order* $r \ge 1$ *with* $m = J^{1/d} - r \ge 0$ *interior knots and uniformly bounded mesh ratio. Then* (a) $\xi_{\psi,J} = 1$ *for all* $J \ge r^d$; (b) *if the density of* X *is uniformly bounded away from* 0 *and* ∞ *on* $[0,1]^d$, *then there exist finite positive constants* c_ψ *and* C_ψ *such that* $c_\psi J \le \lambda_{\max}(G_\psi)^{-1} \le \lambda_{\min}(G_\psi)^{-1} \le C_\psi J$ *for all* $J \ge r^d$; (c) $\lambda_{\max}(G_\psi)/\lambda_{\min}(G_\psi) \le C_\psi/c_\psi$ *for all* $J \ge r^d$.

E.2 *Wavelet bases*

We construct a univariate wavelet basis with support $[0,1]$ following Cohen, Daubechies, and Vial (1993) (CDV hereafter). Let (φ, ψ) be a Daubechies pair such that φ has support $[-N+1, N]$. Given j such that $2^j - 2N > 0$, the orthonormal (with respect to the $L^2([0,1])$ inner product) basis for the space V_j includes $2^j - 2N$ interior scaling functions of the form $\varphi_{j,k}(x) = 2^{j/2}\varphi(2^j x - k)$, each of which has support $[2^{-j}(-N+1+k), 2^{-j}(N+k)]$ for $k = N, \dots, 2^j - N - 1$. These are augmented with N left scaling functions of the form $\varphi^0_{j,k}(x) = 2^{j/2}\varphi^l_k(2^j x)$ for $k = 0, \dots, N-1$ (where $\varphi^l_0, \dots, \varphi^l_{N-1}$ are fixed independent of j), each of which has support $[0, 2^{-j}(N+k)]$, and N right scaling functions of the form $\varphi_{j,2^j-k}(x) = 2^{j/2}\varphi^r_{-k}(2^j(x-1))$ for $k = 1, \dots, N$ (where $\varphi^r_{-1}, \dots, \varphi^r_{-N}$ are fixed independent of j), each of which has support $[1 - 2^{-j}(1-N-k), 1]$. The resulting 2^j functions $\varphi^0_{j,0}, \dots, \varphi^0_{j,N-1}, \varphi_{j,N}, \dots, \varphi_{j,2^j-N-1}, \varphi^1_{j,2^j-N}, \dots, \varphi^1_{j,2^j-1}$ form an orthonormal basis (with respect to the $L^2([0,1])$ inner product) for their closed linear span V_j.

An orthonormal wavelet basis for the space W_j, defined as the orthogonal complement of V_j in V_{j+1}, is similarly constructed from the mother wavelet. This results in an orthonormal basis of 2^j functions, denoted $\psi^0_{j,0}, \dots, \psi^0_{j,N-1}, \psi_{j,N}, \dots, \psi_{j,2^j-N-1}, \psi^1_{j,2^j-N}, \dots, \psi^1_{j,2^j-1}$ (we use this conventional notation without confusion with the ψ_{Jj} basis functions spanning Ψ_J), where the "interior" wavelets $\psi_{j,N}, \dots, \psi_{j,2^j-N-1}$ are of the form $\psi_{j,k}(x) = 2^{j/2}\psi(2^j x - k)$. To simplify notation, we ignore the 0 and 1 superscripts on the left and right wavelets and the scaling functions henceforth. Let L_0 and L be integers such that $2N < 2^{L_0} \le 2^L$. A wavelet space at resolution level L is the 2^{L+1}-dimensional set of functions given by

$$\mathrm{Wav}\big(L, [0,1]\big) = \left\{ \sum_{k=0}^{2^{L_0}-1} a_{L_0,k}\varphi_{L_0,k} + \sum_{j=L_0}^{L} \sum_{k=0}^{2^j-1} b_{j,k}\psi_{j,k} : a_{L_0,k}, b_{j,k} \in \mathbb{R} \right\}.$$

We say that $\mathrm{Wav}(L,[0,1])$ has *regularity* γ if $\psi \in C^\gamma$ (which can be achieved by choosing N sufficiently large) and write $\mathrm{Wav}(L,[0,1],\gamma)$ for a wavelet space of regularity γ with continuously differentiable basis functions.

We construct wavelet bases for $[0,1]^d$ by taking tensor products of univariate bases. We again take L_0 and L to be integers such that $2N < 2^{L_0} \le 2^L$. Let $\widetilde{\psi}_{j,k,G}(x)$ denote an orthonormal tensor-product wavelet for $L^2([0,1]^d)$ at resolution level j, where $k =$

$(k_1, \ldots, k_d) \in \{0, \ldots, 2^j - 1\}^d$ and where $G \in G_{j,L} \subseteq \{w_\varphi, w_\psi\}^d$ denotes which elements of the tensor product are ψ_{j,k_i} (indices corresponding to w_ψ) and which are φ_{j,k_i} (indices corresponding to w_φ). For example, $\widetilde{\psi}_{j,k,w_\psi^d} = \prod_{i=1}^d \psi_{j,k_i}(x_i)$. Note that each $G \in G_{j,L}$ with $j > L$ has an element that is w_ψ (see Triebel (2006) for details). We have $\#(G_{L_0,L_0}) = 2^d$ and $\#(G_{j,L_0}) = 2^d - 1$ for $j > L_0$. Let $\mathrm{Wav}(L, [0,1]^d, \gamma)$ denote the space

$$\mathrm{Wav}\big(L, [0,1]^d, \gamma\big) = \left\{ \sum_{j=L_0}^{L} \sum_{G \in G_{j,L_0}} \sum_{k \in \{0,\ldots,2^j-1\}^d} a_{j,k,G} \widetilde{\psi}_{j,k,G} : a_{j,k,G} \in \mathbb{R} \right\}, \tag{25}$$

where each univariate basis has regularity γ. This definition clearly reduces to the above definition for $\mathrm{Wav}(L, [0,1], \gamma)$ in the univariate case.

Stability properties The following two lemmas bound $\xi_{\psi,J}$, as well as the minimum eigenvalue and condition number of $G_\psi = G_{\psi,J} = E[\psi^J(X_i)\psi^J(X_i)']$ when $\psi_{J1}, \ldots, \psi_{JJ}$ is constructed using univariate and tensor products of CDV wavelet bases.

LEMMA E.3. *Let X have support* $[0,1]$ *and let be a univariate CDV wavelet basis of resolution level $L = \log_2(J) - 1$. Then* (a) $\xi_{\psi,J} = O(\sqrt{J})$ *for each sieve dimension $J = 2^{L+1}$*, (b) *if the density of X is uniformly bounded away from* 0 *and* ∞ *on* $[0,1]$, *then there exists finite positive constants c_ψ and C_ψ such that $c_\psi \le \lambda_{\max}(G_\psi)^{-1} \le \lambda_{\min}(G_\psi)^{-1} \le C_\psi$ for each J, and* (c) $\lambda_{\max}(G_\psi)/\lambda_{\min}(G_\psi) \le C_\psi/c_\psi$ *for each J.*

LEMMA E.4. *Let X have support* $[0,1]^d$ *and let $\psi_{J1}, \ldots, \psi_{JJ}$ be a wavelet basis formed as the tensor product of d univariate bases of resolution level L. Then* (a) $\xi_{\psi,J} = O(\sqrt{J})$ *each J,* (b) *if the density of X is uniformly bounded away from* 0 *and* ∞ *on* $[0,1]^d$, *then there exists finite positive constants c_ψ and C_ψ such that $c_\psi \le \lambda_{\max}(G_\psi)^{-1} \le \lambda_{\min}(G_\psi)^{-1} \le C_\psi$ for each J, and* (c) $\lambda_{\max}(G_\psi)/\lambda_{\min}(G_\psi) \le C_\psi/c_\psi$ *for each J.*

Wavelet characterization of Besov norms When the wavelet basis just described is of regularity $\gamma > 0$, the norms $\|\cdot\|_{B^p_{\infty,\infty}}$ for $p < \gamma$ can be restated in terms of the wavelet coefficients. We briefly explain the multivariate case as it nests the univariate case. Any $f \in L^2([0,1]^d)$ may be represented as

$$f = \sum_{j,G,k} a_{j,k,G}(f)\widetilde{\psi}_{j,k,G},$$

where the sum is understood to be taken over the same indices as in display (25). If $f \in B^p_{\infty,\infty}([0,1]^d)$, then

$$\|f\|_{B^p_{\infty,\infty}} \asymp \|f\|_{b^p_{\infty,\infty}} := \sup_{j,k,G} 2^{j(p+d/2)}\big|a_{j,k,G}(f)\big|,$$

and if $f \in B^p_{2,2}([0,1])$, then

$$\|f\|^2_{B^p_{2,2}} \asymp \|f\|^2_{b^p_{2,2}} := \sum_{j,k,G} 2^{jp} a_{j,k,G}(f)^2.$$

See Johnstone (2013) and Triebel (2006) for more thorough discussions.

Appendix F: Useful results on random matrices

Notation. For a $r \times c$ matrix A with $r \le c$ and full row rank r, we let A_l^- denote its left pseudoinverse, namely $(A'A)^- A'$, where the prime ($'$) denotes transpose and the bar ($^-$) denotes generalized inverse. We let $s_{\min}(A)$ denote the minimum singular value of a rectangular matrix A. For a positive-definite symmetric matrix A, we let $\lambda_{\min}(A)$ and $\lambda_{\max}(A)$ denote its minimum and maximum eigenvalue, respectively.

F.1 *Some matrix inequalities*

The following lemmas are used throughout the proofs in this paper and are stated here for convenience.

Lemma F.1 (Weyl's inequality). *Let $A, B \in \mathbb{R}^{r\times c}$, and let $s_i(A)$ and $s_i(B)$ denote the ith (ordered) singular value of A and B, respectively, for $1 \le i \le (r \wedge c)$. Then $|s_i(A) - s_i(B)| \le \|A - B\|_{\ell^2}$ for all $1 \le i \le (r\wedge c)$. In particular, $|s_{\min}(A) - s_{\min}(B)| \le \|A - B\|_{\ell^2}$.*

Lemma F.2. *Let $A \in \mathbb{R}^{r\times r}$ be nonsingular. Then $\|A^{-1} - I_r\|_{\ell^2} \le \|A^{-1}\|_{\ell^2}\|A - I_r\|_{\ell^2}$.*

Lemma F.3 (Schmitt (1992)). *Let $A, B \in \mathbb{R}^{r\times r}$ be positive definite. Then*

$$\|A^{1/2} - B^{1/2}\|_{\ell^2} \le \frac{1}{\sqrt{\lambda_{\min}(B)} + \sqrt{\lambda_{\min}(A)}}\|A - B\|_{\ell^2}.$$

Lemma F.4. *Let $A, B \in \mathbb{R}^{r\times c}$ with $r \le c$, and let A and B have full row rank r. Then*

$$\|B_l^- - A_l^-\|_{\ell^2} \le \frac{1+\sqrt{5}}{2}\big(s_{\min}(A)^{-2} \vee s_{\min}(B)^{-2}\big)\|A - B\|_{\ell^2}.$$

If, in addition, $\|A - B\|_{\ell^2} \le \frac{1}{2}s_{\min}(A)$, then

$$\|B_l^- - A_l^-\|_{\ell^2} \le 2(1+\sqrt{5})s_{\min}(A)^{-2}\|A - B\|_{\ell^2}.$$

Lemma F.5. *Let $A \in \mathbb{R}^{r\times c}$ with $r \le c$ have full row rank r. Then $\|A_l^-\|_{\ell^2} \le s_{\min}(A)^{-1}$.*

Lemma F.6. *Let $A, B \in \mathbb{R}^{r\times c}$ with $r \le c$, and let A and B have full row rank r. Then*

$$\|A'(AA')^{-1}A - B'(BB')^{-1}B\|_{\ell^2} \le \big(s_{\min}(A)^{-1} \vee s_{\min}(B)^{-1}\big)\|A - B\|_{\ell^2}.$$

F.2 *Convergence of the matrix estimators*

Before presenting the following lemmas, we define the *orthonormalized* matrix estimators

$$\widehat{G}_b^o = G_b^{-1/2}\widehat{G}_b G_b^{-1/2},$$

$$\widehat{G}_\psi^o = G_\psi^{-1/2}\widehat{G}_\psi G_\psi^{-1/2},$$

$$\widehat{S}^o = G_b^{-1/2}\widehat{S} G_\psi^{-1/2},$$

and let $G_b^o = I_K$, $G_\psi^o = I_J$, and S^o denote their respective expected values.

Lemma F.7. *The orthonormalized matrix estimators satisfy the exponential inequalities*

$$\mathbb{P}\big(\|\widehat{G}^o_\psi - G^o_\psi\|_{\ell^2} > t\big) \le 2\exp\left\{\log J - \frac{t^2/2}{\zeta^2_{\psi,J}(1+2t/3)/n}\right\},$$

$$\mathbb{P}\big(\|\widehat{G}^o_b - G^o_b\|_{\ell^2} > t\big) \le 2\exp\left\{\log K - \frac{t^2/2}{\zeta^2_{b,K}(1+2t/3)/n}\right\},$$

$$\mathbb{P}\big(\|\widehat{S}^o - S^o\|_{\ell^2} > t\big) \le 2\exp\left\{\log K - \frac{t^2/2}{(\zeta^2_{b,K}\vee\zeta^2_{\psi,J})/n + 2\zeta_{b,K}\zeta_{\psi,J}t/(3n)}\right\}$$

and, therefore,

$$\|\widehat{G}^o_\psi - G^o_\psi\|_{\ell^2} = O_p\big(\zeta_{\psi,J}\sqrt{(\log J)/n}\big),$$
$$\|\widehat{G}^o_b - G^o_b\|_{\ell^2} = O_p\big(\zeta_{b,K}\sqrt{(\log K)/n}\big),$$
$$\|\widehat{S}^o - S^o\|_{\ell^2} = O_p\big((\zeta_{b,K}\vee\zeta_{\psi,J})\sqrt{(\log K)/n}\big)$$

as $n, J, K \to \infty$ *provided* $(\zeta_{b,K}\vee\zeta_{\psi,J})\sqrt{(\log K)/n} = o(1)$.

Lemma F.8 (Newey (1997, p. 162)). *Let Assumption* 2(i) *hold. Then* $\|G_b^{-1/2}B'u/n\|_{\ell^2} = O_p(\sqrt{K/n})$.

Lemma F.9. *Let* $h_J(x) = \psi^J(x)'c_J$ *for any deterministic* $c_J \in \mathbb{R}^J$ *and let* $H_J = (h_J(X_1), \dots, h_J(X_n))' = \Psi c_J$. *Then*

$$\begin{aligned}&\big\|G_b^{-1/2}\big(B'(H_0 - \Psi c_J)/n - E\big[b^K(W_i)\big(h_0(X_i) - h_J(X_i)\big)\big]\big)\big\|_{\ell^2}\\ &= O_p\big(\big(\sqrt{K/n}\times\|h_0 - h_J\|_\infty\big)\wedge\big(\zeta_{b,K}/\sqrt{n}\times\|h_0 - h_J\|_{L^2(X)}\big)\big).\end{aligned}$$

Lemma F.10. *Let* $s_{JK}^{-1}\zeta\sqrt{(\log J)/n} = o(1)$ *and let* $J \le K = O(J)$. *Then*

(a) $\big\|\big(\widehat{G}_b^{-1/2}\widehat{S}\big)_l^-\widehat{G}_b^{-1/2}G_b^{1/2} - \big(G_b^{-1/2}S\big)_l^-\big\|_{\ell^2} = O_p\big(s_{JK}^{-2}\zeta\sqrt{(\log J)/(ne_J)}\big)$,

(b) $\big\|G_\psi^{1/2}\big\{\big(\widehat{G}_b^{-1/2}\widehat{S}\big)_l^-\widehat{G}_b^{-1/2}G_b^{1/2} - \big(G_b^{-1/2}S\big)_l^-\big\}\big\|_{\ell^2} = O_p\big(s_{JK}^{-2}\zeta\sqrt{(\log J)/n}\big)$,

(c) $\big\|G_b^{-1/2}S\big\{\big(\widehat{G}_b^{-1/2}\widehat{S}\big)_l^-\widehat{G}_b^{-1/2}G_b^{1/2} - \big(G_b^{-1/2}S\big)_l^-\big\}\big\|_{\ell^2} = O_p\big(s_{JK}^{-1}\zeta\sqrt{(\log J)/n}\big)$.

References

Chen, X. and T. M. Christensen (2015), "Optimal uniform convergence rates and asymptotic normality for series estimators under weak dependence and weak conditions." *Journal of Econometrics*, 188 (2), 447–465. [3]

Chen, X. and D. Pouzo (2015), "Sieve Wald and QLR inferences on semi/nonparametric conditional moment models." *Econometrica*, 83 (3), 1013–1079. [1, 2, 3]

Cohen, A., I. Daubechies, and P. Vial (1993), "Wavelets on the interval and fast wavelet transforms." *Applied and Computational Harmonic Analysis*, 1, 54–81. [5]

DeVore, R. A. and G. G. Lorentz (1993), *Constructive Approximation*. Grundlehren der mathematischen Wissenschaften, Vol. 303. Springer-Verlag, Berlin. [4]

Johnstone, I. M. (2013), "Gaussian estimation: Sequence and wavelet models." Manuscript. [6]

Newey, W. K. (1997), "Convergence rates and asymptotic normality for series estimators." *Journal of Econometrics*, 79 (1), 147–168. [8]

Schmitt, B. A. (1992), "Perturbation bounds for matrix square roots and Pythagorean sums." *Linear Algebra and its Applications*, 174 (0), 215–227. [7]

Triebel, H. (2006), *Theory of Function Spaces III*. Birkhäuser, Basel. [6]

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