Fluctuations of Linear Eigenvalue Statistics of Random Band Matrices

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13th December, 2014

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Define a real symmetric random band matrix $M = (m_{jk})_{n \times n}$ of bandwidth $b_n$ as

$$m_{jk} = m_{k,j} = \begin{cases} b_n^{-1/2} w_{jk} & \text{if } d_n(j, k) \leq b_n \\ 0 & \text{otherwise,} \end{cases}$$

(1)

where $d_n(j, k) := \min\{|j - k|, n - |j - k|\}$ and $\{w_{jk}\}_{j \leq k}$ is a sequence of independent real random variables with

$$\mathbb{E}[w_{jk}] = 0, \quad \mathbb{E}[w_{jk}^2] = \begin{cases} 1 & \text{if } j \neq k \\ \sigma^2 & \text{if } j = k. \end{cases}$$

(2)
Let $\lambda_1 \leq \lambda_2 \leq \cdots \leq \lambda_n$ be the eigenvalues of the random band matrix $M$. Define the linear eigenvalue statistic of the eigenvalues of $M$ as

$$\mathcal{N}_n(\phi) = \sum_{i=1}^{n} \phi(\lambda_i),$$

(3)

and the normalized eigenvalue statistic of the matrix $M$ as

$$\mathcal{M}_n(\phi) = \sqrt{b_n \frac{n}{n}} \mathcal{N}_n(\phi),$$

(4)

where $\phi$ is a test function.
Theorem

Let $M$ be a real symmetric random band matrix as defined in (1), and $b_n$ be a sequence of integers satisfying $\sqrt{n} \ll b_n \ll n$. Assume the following:

(i) The probability distribution of $w_{jk}$ satisfies the Poincaré inequality with some uniform constant $m$ which does not depend on $n, j, k$.

(ii) $E[w_{jk}^4] = \mu_4$ for all $d_n(j, k) \leq b_n$.

(iii) $\phi : \mathbb{R} \to \mathbb{R}$ be a test function in the Sobolev space $H^s$ i.e., $\|\phi\|_s < \infty$, where

$$\|\phi\|^2_s = \int_{\mathbb{R}} (1 + 2|t|)^{2s} |\hat{\phi}(t)|^2 \, dt,$$

$$\hat{\phi}(t) = \frac{1}{\sqrt{2\pi}} \int_{\mathbb{R}} e^{-it\lambda} \phi(\lambda) \, d\lambda,$$

and $s > 5/2$. 
Then the centred normalized eigenvalue statistic $M^\circ(\phi) = M_n(\phi) - \mathbb{E}[M_n(\phi)]$ converges in distribution to the Gaussian random variable with mean zero and variance given by

$$V(\phi) = \frac{\kappa_4}{16\pi^2} \left( \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{4 - \mu^2}{\sqrt{8 - \mu^2}} \phi(\mu) \, d\mu \right)^2 + \frac{\sigma^2}{16\pi^2} \left( \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{\mu\phi(\mu)}{\sqrt{8 - \mu^2}} \, d\mu \right)^2$$

$$+ \int_{-2\sqrt{2}}^{2\sqrt{2}} \int_{-2\sqrt{2}}^{2\sqrt{2}} \sqrt{(8 - x^2)(8 - y^2)} F(x, y) \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{\mu_1\phi(\mu_1)}{(x - \mu_1)\sqrt{8 - \mu_1^2}} \frac{\mu_2\phi(\mu_2)}{(x - \mu_2)^2\sqrt{8 - \mu_2^2}} \, d\mu_1 d\mu_2 \, dx \, dy,$$

where for $x \neq y$

$$F(x, y) = \sqrt{2} \int_{-\infty}^{\infty} \frac{(s^3 \sin s - s \sin^3 s)}{2(s^2 - \sin^2 s)^2 - (s^3 \sin s + s \sin^3 s)xy + s^2 \sin^2 s(x^2 + y^2)} \, ds,$$

and $\kappa_4$ is the fourth cumulant of the off-diagonal entries, i.e., $\kappa_4 = \mathbb{E}[W_{12}^4] - 3$. 
Proof | Step 1 | Approximate $\phi$ by smooth functions

Define $e_n(x) = e^{ixM_n^\circ(\phi)}$, and $Z_n(x) = \mathbb{E}[e_n(x)]$. We want to show that

$$\lim_{n \to \infty} Z_n(x) = \exp \left[-\frac{x^2V(\phi)}{2}\right] \quad \forall \ x \in \mathbb{R}.$$ 

For any test function $\phi \in H^s$, define

$$P_\eta(x) = \frac{\eta}{\pi(x^2 + \eta^2)}, \quad \phi_\eta = P_\eta * \phi.$$ 

At this moment, denote $Z_n(\phi) := Z_n(x)$. Using proposition 1, 2 and the fact that $\|\phi - \phi_\eta\|_s \to 0$ as $\eta \downarrow 0$, we have

$$\lim_{\eta \downarrow 0} (Z_n(\phi) - Z_n(\phi_\eta)) = 0.$$ 

Then for any converging subsequence $\{Z_{n_j}(\phi)\}_{j=1}^\infty$ we have

$$\lim_{n_j \to \infty} Z_{n_j}(\phi) = \lim_{\eta \downarrow 0} \lim_{n_j \to \infty} Z_{n_j}(\phi_\eta).$$
Proof | Step 2 | The differential equation satisfied by $Z_n(\phi_\eta)$

$$\frac{d}{dx} Z_n(\phi_\eta) = \frac{d}{dx} \mathbb{E} \left[ \exp \left( ix \sqrt{\frac{b_n}{n}} N_n^\circ(\phi_\eta) \right) \right] = \frac{1}{2\pi} \sqrt{\frac{b_n}{n}} \int_{-\infty}^{\infty} \phi(\mu) \left( Y_n(z_\mu, x) - Y_n(z_\bar{\mu}, x) \right) d\mu,$$

where $Y_n(z_\mu, x) = \mathbb{E}[e_{\eta,n}(x) \text{Tr}(G^\circ(z_\mu))]$, $G(z) = \text{Tr}(M - zI)^{-1}$, $e_{\eta,n}(x) = \exp \left( ix \sqrt{\frac{b_n}{n}} N_n^\circ(\phi_\eta) \right)$, $\mu = \mathcal{S}(z_\mu)$, and $X^\circ = X - \mathbb{E}[X]$. 
Proof | Step 3 | Estimation of $Y_n(z_{\mu}, x)$

\[
Y_n(z, x) = Z_n(\phi_\eta) \frac{x}{2\pi} \sqrt{\frac{n}{b_n}} \int_{-\infty}^{\infty} (C_n(z, z_\mu) - C_n(z, \bar{z}_\mu)) \phi(\mu) \, d\mu,
\]

where $C_n(z, z_\mu)$ is written on the next page. Then we have

\[
\frac{d}{dx} Z_n(\phi_\eta) = \frac{1}{2\pi} \sqrt{\frac{b_n}{n}} \int_{-\infty}^{\infty} \phi(\mu) (Y_n(z_\mu, x) - Y_n(\bar{z}_\mu, x)) \, d\mu
\]

\[
= -x Z_n(\phi_\eta) V_n(\phi, \eta),
\]

where

\[
V_n(\phi, \eta) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \phi(\mu_1) \phi(\mu_2) [C_n(z_{\mu_1}, \bar{z}_\mu_2) + C_n(\bar{z}_\mu_1, z_{\mu_2})
- C_n(z_{\mu_1}, z_{\mu_2}) - C_n(\bar{z}_\mu_1, \bar{z}_\mu_2)] \, d\mu_2 d\mu_1
\]  

(5)
\[
\lim_{n \to \infty} C_n(z_{\mu_1}, z_{\mu_2}) = \frac{1}{1 - 2f^2(z_{\mu_1})} \left[ f^2(z_{\mu_1})f^2(z_{\mu_2})(1 + 2f'(z_{\mu_2})) \lim_{n \to \infty} \mathbb{E}[T_n] \\
+ f^2(z_{\mu_1})f(z_{\mu_2}) \lim_{n \to \infty} \frac{d}{dz_{\mu_2}} \mathbb{E}[T_n] + \sigma^2 f^2(z_{\mu_1})f^2(z_{\mu_2})(1 + 2f'(z_{\mu_2})) \\
+ 2\kappa_4 \left\{ f^3(z_{\mu_1})f^3(z_{\mu_2})(1 + 2f'(z_{\mu_2})) + f^3(z_{\mu_1})f(z_{\mu_2})f'(z_{\mu_2}) \right\} \right] (6)
\]

where

\[
T_n = \frac{2}{b_n} \sum_{i,j \in I_1} G^{(1)}_{ij}(z)G^{(1)}_{ij}(z_{\mu}),
\]

\[
G^{(1)}(z_{\mu}) = \left( M^{(1)} - z_{\mu}I \right)^{-1},
\]

\[
I_1 = \{ 1 < i \leq n : d_n(1, i) \leq b_n \},
\]

and \( M^{(1)} \) is the main bottom \((n - 1) \times (n - 1)\) minor of \( M \).
Combining (5), (6), and Proposition 3 we have

\[ V(\phi) = \lim_{\eta \downarrow 0} \lim_{n \to \infty} V_n(\phi, \eta) = \frac{\kappa_4}{16\pi^2} \left( \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{4 - \mu^2}{\sqrt{8 - \mu^2}} \phi(\mu) \, d\mu \right)^2 + \frac{\sigma^2}{16\pi^2} \left( \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{\mu \phi(\mu)}{\sqrt{8 - \mu^2}} \, d\mu \right) \]

\[ + \int_{-2\sqrt{2}}^{2\sqrt{2}} \int_{-2\sqrt{2}}^{2\sqrt{2}} \sqrt{(8 - x^2)(8 - y^2)} \tilde{F}(x, y) \int_{-2\sqrt{2}}^{2\sqrt{2}} \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{\mu_1 \phi(\mu_1)}{(x - \mu_1) \sqrt{8 - \mu_1^2}} \frac{\mu_2 \phi(\mu_2)}{(x - \mu_2)^2 \sqrt{8 - \mu_2^2}} \, d\mu_1 d\mu_2 \, dx \, dy. \]
Proposition 1*

Let $M$ be an $n \times n$ random matrix and $\mathcal{N}_n(\phi)$ be a linear eigenvalue statistic of its eigenvalue as in (3). Then for any $s > 0$ we have

$$\text{Var}[\mathcal{N}_n(\phi)] \leq C_s \|\phi\|^2_s \int_0^\infty dy \, e^{-y} y^{2s-1} \int_{-\infty}^\infty \text{Var}[\text{Tr}(G(x + iy))] \, dx,$$

where $C_s$ is a constant depends only on $s$, and $G(z) = (M - zI)^{-1}$, is the resolvent of the matrix $M$.

Proposition 2

Consider symmetric band matrix $M$ defined in (1) and assume (2) is satisfied. Then

$$\text{Var}\{\gamma_n\} \leq \frac{C}{b_n} \left( |\Re z|^{-2} + |\Im z|^{-4} \right) \sum_{i=1}^n \mathbb{E}[|G_{ii}|^2] \quad (8)$$

where $\gamma_n = \text{Tr}(M - zI)^{-1} = \text{Tr}(G(z))$. 
Proposition 3

Let $T_n$ be as defined in (7). Then

$$\lim_{n \to \infty} \mathbb{E}[T_n] = \frac{1}{4\pi^3} \int_{-2\sqrt{2}}^{2\sqrt{2}} \int_{-2\sqrt{2}}^{2\sqrt{2}} \frac{\sqrt{8 - x^2} \sqrt{8 - y^2}}{(x - z)(y - z \mu)} \tilde{F}(x, y) 1_{\{x \neq y\}} \, dx \, dy,$$

where

$$\tilde{F}(x, y) = \sqrt{2} \int_{-\infty}^{\infty} \frac{u(u - u^3)}{2(1 - u^2) + u^2(x^2 + y^2) - u(1 + u^2)} \, ds,$$

and $u = \frac{\sin s}{s}$. 
MATLAB Results

Figure: The eigenvalue statistics was sampled 400 times. The test function was $\phi(x) = \sqrt{16 - x^2}$.

(a) $n = 2000$, $b_n = n^{0.2}$. Fourth moment/(variance)$^2 = 2.92$

(b) $n = 2000$, $b_n = n^{0.8}$. Fourth moment/(variance)$^2 = 2.91$
In the following example we had taken a different test function.

\[
\phi(x) = e^{-x^2}
\]

(a) \( n = 2000, b_n = n^{0.2} \). Fourth moment/(variance)\(^2\)=3.08

(b) \( n = 2000, b_n = n^{0.8} \). Fourth moment/(variance)\(^2\)=3.08

Figure: The eigenvalue statistics was sampled 400 times. The test function was \( \phi(x) = e^{-x^2} \).
References:
*For the proof of Proposition 1 see the references below

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