

Generalized tensor response regression with multilinear features

1 Preliminaries

Let $\mathcal{Y} = \llbracket y_{i_1, \dots, i_K} \rrbracket \in \mathbb{R}^{d_1 \times \dots \times d_K}$ be an order- K tensor, and $\mathbf{X}_k \in \mathbb{R}^{d_k \times p_k}$ be the features along the k -th mode.

$$f(\mathbb{E}(\mathcal{Y} | \mathbf{X}_1, \dots, \mathbf{X}_K)) = \mathcal{B} \times_1 \mathbf{X}_1 \times_2 \dots \times_K \mathbf{X}_K$$

where $f(\cdot)$ is the inverse link function which is assumed to be applied to tensors in an entry-wise manner. Here $\mathcal{B} \in \mathbb{R}^{p_1 \times \dots \times p_K}$ is the unknown parameter tensor of interest.

$$\mathcal{Y} | \mathbf{X}_1, \dots, \mathbf{X}_K \stackrel{\text{in D.}}{\sim} \exp \left(\langle \mathcal{Y}, \mathcal{U} \rangle - \sum_{i_1, \dots, i_K} b(u_{i_1, \dots, i_K}) \right) \prod_{i_1, \dots, i_K} h(y_{i_1, \dots, i_K})$$

$$\text{where } \mathcal{U} = \mathcal{B} \times_1 \mathbf{X}_1 \times_2 \dots \times_K \mathbf{X}_K$$

where $b'(\cdot)$ is a link function and $\mathcal{U} = \llbracket u_{i_1, \dots, i_K} \rrbracket$ is the canonical parameter

$$\mathbb{E}(y_{i_1, \dots, i_K} | \mathbf{X}_1, \dots, \mathbf{X}_K) = b'(u_{i_1, \dots, i_K}) = \mathcal{B} \times_1 \mathbf{X}_1 \times_2 \dots \times_K \mathbf{X}_K$$

2 Model

Suppose that the response tensor $\mathcal{Y} = \llbracket Y_{i_1, \dots, i_K} \rrbracket$ follows an exponential family distribution:

$$f(\mathcal{Y} | \Theta) = \prod_{i_1, \dots, i_K} f(y_{i_1, \dots, i_K} | \Theta) = \prod_{i_1, \dots, i_K} c(y_{i_1, \dots, i_K}) \exp \left(\frac{y_{i_1, \dots, i_K} \theta_{i_1, \dots, i_K} - b(\theta_{i_1, \dots, i_K})}{\phi} \right).$$

Here ϕ is a constant, $c(\cdot)$ and $b(\cdot)$ are known functions, and $\Theta = \llbracket \theta_{i_1, \dots, i_K} \rrbracket$ collects the linear predictors

$$\Theta = \Theta(\mathcal{B}, \mathcal{X}) = \mathcal{B} \times_1 \mathbf{X}_1 \times_2 \dots \times_K \mathbf{X}_K, \quad \text{rank}(\mathcal{B}) \leq (r_1, \dots, r_K),$$

where $\mathcal{B} \in \mathbb{R}^{p_1 \times \dots \times p_K}$ is the unknown coefficient tensor of interest.

	$b(\theta)$	$b'(\theta)$	$c(\theta)$	ϕ
Normal	$\frac{1}{2}\theta^2$	θ	...	σ^2
Bernoulli		$\frac{1}{1+e^{-\theta}}$...	1
Poisson	e^θ	e^θ	...	1

The log-likelihood for the coefficient tensor \mathcal{B} is given, up to an affine transformation, by

$$\mathcal{L}_{\mathcal{Y}}(\mathcal{B}) = \langle \mathcal{Y}, \Theta \rangle - \sum_{i_1, \dots, i_K} b(\theta_{i_1, \dots, i_K}), \quad \text{where} \quad \Theta = \mathcal{B} \times_1 \mathbf{X}_1 \times_2 \cdots \times_K \mathbf{X}_K.$$

We propose the constrained MLE:

$$\hat{\mathcal{B}} = \arg \max_{\text{rank}(\mathcal{B}) \leq r} \mathcal{L}_{\mathcal{Y}}(\mathcal{B})$$

Theorem 1. $\|\hat{\mathcal{B}} - \mathcal{B}\|_F^2 \leq w$

Proof. Let $\ell(\mathcal{B}) = \mathbb{E}_{\mathcal{Y} \sim \mathcal{B}_{\text{true}}}(\mathcal{L}_{\mathcal{Y}}(\mathcal{B}))$. We first show that (1) the stochastic deviation $\mathcal{L}_{\mathcal{Y}}(\mathcal{B}) - \ell(\mathcal{B})$ is uniformly small for all \mathcal{B} and (2) $\ell(\hat{\mathcal{B}}) - \ell(\mathcal{B}_{\text{true}}) \approx C\|\hat{\mathcal{B}} - \mathcal{B}_{\text{true}}\|_F^2$.

Note that

$$\begin{aligned} \mathcal{L}_{\mathcal{Y}}(\mathcal{B}) - \ell(\mathcal{B}) &= \langle \mathcal{Y} - \mathbb{E}(\mathcal{Y}|\mathcal{X}), \Theta(\mathcal{B}) \rangle \\ &= \langle \mathcal{Y} - b'(\Theta_{\text{true}}), \Theta \rangle \\ &= \langle \mathcal{E} \times_1 \mathbf{X}_1^T \times_2 \cdots \times_K \mathbf{X}_K^T, \mathcal{B} \rangle, \end{aligned}$$

where $\mathcal{E} = \llbracket \varepsilon_{i_1, \dots, i_K} \rrbracket \stackrel{\text{def}}{=} \mathcal{Y} - b'(\Theta_{\text{true}})$. Based on assumption 1, \mathcal{E} is sub-Gaussian with parameter bounded by ϕM . Therefore $\mathcal{E} \times_1 \mathbf{X}_1^T \times_2 \cdots \times_K \mathbf{X}_K^T$ is a sub-Gaussian with parameter bounded by $\phi M \prod_k \sigma_k(\mathbf{X}_k)$.

Second,

$$\ell(\mathcal{B}) = \ell(\mathcal{B}_{\text{true}}) - \frac{1}{2}(\mathcal{B} - \mathcal{B}_{\text{true}})^T \mathbb{E}(\mathcal{H}_{\mathcal{Y}}(\check{\mathcal{B}}))(\mathcal{B} - \mathcal{B}_{\text{true}})$$

Note that (non-random) Hessian matrix is So

$$\ell(\mathcal{B}) - \ell(\mathcal{B}_{\text{true}}) = -\frac{1}{2} \sum_{i_1, \dots, i_K} b''(\check{\theta}_{i_1, \dots, i_K})(\theta_{i_1, \dots, i_K} - \theta_{\text{true}, i_1, \dots, i_K})^2 \leq -\frac{L}{2} \|\Theta - \Theta_{\text{true}}\|_F^2,$$

holds for all \mathcal{B} , provided that $b''(\theta) \geq L > 0$.

Now consider $\hat{\mathcal{B}}$. Because $\mathcal{L}_{\mathcal{Y}}(\hat{\mathcal{B}}) - \mathcal{L}_{\mathcal{Y}}(\mathcal{B}_{\text{true}}) \geq 0$,

$$\begin{aligned} 0 &\leq \mathcal{L}_{\mathcal{Y}}(\hat{\mathcal{B}}) - \mathcal{L}_{\mathcal{Y}}(\mathcal{B}_{\text{true}}) \\ &\leq \left(\mathcal{L}_{\mathcal{Y}}(\hat{\mathcal{B}}) - \ell(\hat{\mathcal{B}}) \right) - \left(\mathcal{L}_{\mathcal{Y}}(\mathcal{B}_{\text{true}}) - \ell(\mathcal{B}_{\text{true}}) \right) + \left(\ell(\hat{\mathcal{B}}) - \ell(\mathcal{B}_{\text{true}}) \right) \\ &\leq \langle \mathcal{E}, \hat{\Theta} - \Theta_{\text{true}} \rangle - \frac{L}{2} \|\hat{\Theta} - \Theta_{\text{true}}\|_F^2 \end{aligned}$$

$$\|\hat{\Theta} - \Theta_{\text{true}}\|_F \leq \frac{2}{L} \left\langle \mathcal{E}, \frac{\hat{\Theta} - \Theta_{\text{true}}}{\|\hat{\Theta} - \Theta_{\text{true}}\|_F} \right\rangle \leq \frac{2}{L} \sup_{\Theta: \|\Theta\|_F=1, \Theta=\mathcal{B} \times_1 \mathbf{X}_1 \times_2 \cdots \times_K \mathbf{X}_K} \langle \mathcal{E}, \Theta \rangle$$

Therefore,

$$\|\hat{\Theta} - \Theta_{\text{true}}\|_F^2 \leq \frac{2}{L} \sup_{\mathcal{B}} |\mathcal{L}_{\mathcal{Y}}(\mathcal{B}) - \ell(\mathcal{B})|$$

□

Assumption 1. *Consider the following conditions*

- $0 < L \leq b''(\theta) \leq M \leq \infty$ for any $\theta \in \mathbb{R}$