TA Session for Econometrics II 2025

Jukina HATAKEYAMA

The University of Osaka, Department of Economics

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Introduction to Large Sample Test

Framework

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Wald test

ikelihood Ration tes

Just in case... LR

xample

Simulation Experiment

- 1 Introduction to Large Sample Test
- 2 Framework
- 3 tests

Wald test Score test

Likelihood Ration test

Test statistics

Just in case. I R

- Example
- **6** Simulation Experiment

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1 Introduction to Large Sample Test

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TA Session for Econometrics II

Introduction to Large Sample Test

5 Simulation Experiment

Introduction to Large Sample Test

$$y = X\beta + u, \quad u \sim N_{\mathbb{R}^N}(0, \sigma^2 I_N)$$

Objective function:

$$g(\theta|X) = (y - X\beta)^{\top}(y - X\beta)$$

- In the linear regression model, finite-sample inference cannot rely solely on the Gaussian assumption.
- Instead, we use the *t*-distribution or perform an *F*-test.
- But how can we proceed in the case of **non-linear models**?

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Framework

Wald test

Score test Likelihood Ration test

est statistics ust in case... LR

xample

Maximum likelihood estimators satisfy

$$\hat{\theta} \xrightarrow[n \to \infty]{d} N_{\mathbb{R}^k} (\theta_0, I(\theta_0)^{-1}),$$

where $I(\theta_0)$ is the Fisher information matrix.

- This asymptotic normality enables us to construct tests even in non-linear settings.
- Based on this idea, three major tests are developed:
 - Likelihood Ratio Test (LRT)
 - Wald Test
 - Score Test (Lagrange Multiplier Test)

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Introduction to Large Sample Test

Making doubly sure

- Linear regression:
 - Errors are Gaussian.
 - OLS estimator is a linear transformation of errors.
 - \Rightarrow Exact normal distribution for $\hat{\beta}$ (finite n).
- Non-linear models:
 - Parameters are defined via non-linear transformations of data.
 - Finite-sample distribution of $\hat{\beta}$ cannot be derived.
 - Only asymptotic normality (as $n \to \infty$) is available.
- ⇒ We rely on large sample tests.

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Introduction to Large Sample Test

Framework

Weld too

vvaid test

kelihood Ration te

est statistics

....

Example

Simulation

- 1 Introduction to Large Sample Test
- 2 Framework

5 Simulation Experiment

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Framework

Framework

$$y = X\beta + u, \quad u \sim N_{\mathbb{R}^N}(0, \sigma^2 I_N)$$

Let $f_u(u)$ denote the probability density function of u. Since $u = y - X\beta$ is a transformation of y, the likelihood function can be expressed as:

$$L(\theta \mid y, X) = f_u(y - X\beta) \left| \det(\nabla_y u) \right|,$$

where $\nabla_y u = \frac{\partial u}{\partial y}$ is the Jacobian of the transformation from y to u. Thus, the likelihood becomes:

$$L(\beta, \sigma^2 \mid y, X) = (2\pi\sigma^2)^{-N/2} \exp\left[-\frac{1}{2\sigma^2}(y - X\beta)^{\top}(y - X\beta)\right].$$

Taking the logarithm, we obtain the log-likelihood function:

$$\ell(\beta, \sigma^2 \mid y, X) = -\frac{N}{2} \log(2\pi) - \frac{N}{2} \log(\sigma^2) - \frac{1}{2\sigma^2} (y - X\beta)^{\top} (y - X\beta)$$

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Framework

tests

Wald test Score test

ikelihood Ration tes est statistics

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xample

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The statistical criterion is:

$$\hat{\theta} = \arg\max_{\theta} M_n(\theta),$$

where $M_n(\theta)$ is:

$$M_n(\theta) = \frac{1}{N} \sum_{i=1}^{N} \ell_i(\theta), \quad \ell_i(\theta) = \log f(y_i \mid X_i, \theta).$$

Let $\beta = (\beta_1^\top, \beta_2^\top)^\top$ and null hyposesis $H_0: \beta_2 = \beta_{c,2} = 0$.

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Introduction to Large Sample Test

Framework

3 tests

Wald test

kelihood Ration test

ist in case... LR

xample

Simulation Experiment For instance, consider 2 estimators, an unconstrained one:

$$\hat{\theta} = \begin{pmatrix} \hat{\theta_1} \\ \hat{\theta_2} \\ \hat{\sigma^2} \end{pmatrix} = \arg\max_{\theta} M_n(\theta)$$

and a constrained one:

$$\hat{\theta}^0 = \begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_{2,c} \\ \hat{\sigma}^2 \end{pmatrix} = \begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_{2,c} \\ \hat{\sigma}^2 \end{pmatrix} = \arg\max_{\theta} M_n((\beta_1^\top, \beta_{2,c}^\top, \sigma^2))$$

Which estimator provides a better fit under the null?

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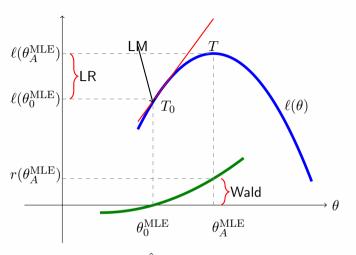
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Wald test

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est statistics est in case... LR

xample



Restriction function $r(\theta)=0$. $M_N(\hat{\theta})$ is the log-likelihood evaluated at the MLE of the restricted model (:under H_0) which corresponds to $\ell(\theta_0^{\rm MLE})$; $M_N(\hat{\theta})$ is the log-likelihood function evaluated at the MLE of the unrestricted model (:under H_1) corresponds to $\ell(\theta_A^{\rm MLE})$

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Framework

Wald test

Score test
Likelihood Ration tes
Test statistics

Fest statistics Just in case... LR

Example

Comparison of Large Sample Tests

• Consider the null hypothesis in the linear model:

$$H_0: \beta_2 = \beta_{2,c}.$$

Here $\theta = (\beta, \sigma^2)$, with $\beta = (\beta_1^\top, \beta_2^\top)^\top \in \mathbb{R}^{k_1 + k_2}$.

1 Likelihood Ratio (LR) Test

$$LR = 2\left[\ell(\hat{\beta}, \hat{\sigma}^2) - \ell(\hat{\beta}^0, \hat{\sigma}^{2,0})\right] \xrightarrow[n \to \infty]{d} \chi^2(k_2),$$

where $(\hat{\beta}, \hat{\sigma}^2)$ is the unrestricted MLE, and $(\hat{\beta}^0, \hat{\sigma}^{2,0})$ the restricted MLE under H_0 .

Wald Test

$$W = (\hat{\beta}_2 - \beta_{2,c})^{\top} \left[\widehat{\operatorname{Var}}(\hat{\beta}_2) \right]^{-1} (\hat{\beta}_2 - \beta_{2,c}) \quad \xrightarrow[n \to \infty]{d} \chi^2(k_2).$$

3 Score (Lagrange Multiplier) Test

$$S = s_{\beta_2}(\hat{\beta}^0, \hat{\sigma}^2)^\top \left[\widehat{\operatorname{Var}}(s_{\beta_2}(\hat{\beta}^0, \hat{\sigma}^2)) \right]^{-1} s_{\beta_2}(\hat{\beta}^0, \hat{\sigma}^2) \quad \xrightarrow[n \to \infty]{d} \chi^2(k_2),$$

where $s_{\beta_2}(\beta, \sigma^2) = \partial \ell(\beta, \sigma^2)/\partial \beta_2$ is the score function with respect to β_2 .

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Framework

ests

core test ikelihood Ration test

Example

experiment

LR Test:

- Compares the maximized log-likelihood under unrestricted vs. restricted models
- Symmetric and invariant to parameterization

• Wald Test:

- Uses the unrestricted estimator $\hat{\theta}$ to test constraints
- Can be unstable if estimator is near the boundary or sample size is small

Score Test:

- Uses only the restricted estimator $\hat{ heta}^0$
- Useful when the unrestricted MLE is difficult to compute
- ullet All three tests are asymptotically equivalent as $n o \infty$

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Introduction to
Large Sample Test

Framework

3 tests

Wald test

Likelihood Ration tes

est statistics

xample

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Introduction to
Large Sample Test

Framework

Wald test

Score test

ikelihood Ration test

ust in case... LF

xample

imulation

experiment

Unconstrained estimates only Wald test

- Tests the validity of the null hypothesis using the unconstrained estimator
- Constrained estimates only Score (Lagrange Multiplier) test
 - Tests whether relaxing the restriction improves the fit, based on the constrained estimator
- Both constrained and unconstrained estimates Likelihood Ratio test
 - Compares the fit of the model with and without the restriction

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Framework

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kelihood Ration test

est statistics

Example

Experiment

All the following asymptotic distributions are based on:

$$\sqrt{n}(\hat{\theta} - \theta_0) \xrightarrow[n \to \infty]{d} N_{\mathbb{R}^N}(0, H(\theta_0)^{-1}J(\theta_0)H(\theta_0)^{-1}).$$

These tests hold for any M-estimator.

- 1 Introduction to Large Sample Test
- 2 Framework
- 3 tests

Wald test
Score test
Likelihood Ration test
Test statistics
Just in case J.R.

- 4 Example
- 5 Simulation Experiment

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Introduction to Large Sample Test

-ramework

3 tests

Wald tos

Score test

ikelihood Ration tes Fast statistics

Just in case... LI

xample

Simulation Experiment

Wald test

 $H_0: r(\theta_0) = 0$ with $r: \mathbb{R}^d \to \mathbb{R}^L$ where $L \leq d$.

 \Rightarrow we want to check whether $r(\hat{\theta})$ is close to zero or not.

$$\hat{\theta} = \underset{\theta}{\operatorname{arg}} \max_{\theta} M_n(\theta) = \underset{\theta}{\operatorname{arg}} \max_{n} \frac{1}{n} \sum_{i=1}^n \ell(X_i, \theta)$$

Theorem

Under H_0 , the statistic of the Wald test, $\zeta_n^W = nr(\hat{\theta})\Sigma_W^{-1}(\hat{\theta})r(\hat{\theta})$, is asymptotically distributed as $\xi^s(L)$ with:

$$\Sigma_W(\hat{\theta}) = (\nabla_{\theta} r(\hat{\theta}))^{\top} \hat{H}^{-1}(\hat{\theta}) \hat{J}(\hat{\theta}) \hat{H}^{-1}(\hat{\theta}) (\nabla_{\theta} r(\hat{\theta})),$$

$$\Sigma_W(\theta_0) = (\nabla_{\theta} r(\theta_0))^{\top} \hat{H}^{-1}(\theta_0) \hat{J}(\theta_0) \hat{H}^{-1}(\theta_0) (\nabla_{\theta} r(\theta_0)),$$

$$H(\theta) = \mathbb{E}[\nabla^2_{\theta\theta^{\top}}\ell(X_i,\theta)]$$
, and $J(\theta) = \mathbb{E}[\nabla_{\theta}\ell(X_i,\theta)\nabla_{\theta^{\top}}\ell(X_i,\theta)]$ with $\hat{H}(\hat{\theta})$ and $\hat{J}(\hat{\theta})$ aonsistent estimators of $H(\theta)$ and $J(\theta)$. The test with rejection area $RA = \{\zeta_n^W : \zeta_n^W \geq q_{1-\alpha}(\xi^2(L))\}$ has an asymptotic level α .

$$\nabla_{\theta} r(\theta))^{\top}$$
 is the Jacobian matrix of the size $L \times d$.

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tests

Wald test Score test

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Score test (Lagrange Multiplier test)

$$\widehat{ heta^0} = rg \max_{ heta} \! M_n(heta)$$
 subject to the constraints.

 \Rightarrow we want to check whether $\nabla_\theta M_n(\widehat{\theta^0})$ is close to zero or not. Assume $J(\theta)=H(\theta).$

Theorem

Under H_0 , the statistic of score test, $\zeta_n^S = n(\nabla_\theta M_n(\widehat{\theta^0}))^\top \hat{H}^{-1}(\widehat{\theta^0}) \nabla_\theta M_n(\widehat{\theta^0})$, satisfies below:

$$\zeta_n^S = \zeta_n^W + o_p(1).$$

The Score test does not involve the unconstrained estimator.

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Introduction to Large Sample Test

Framework

tests

Wald test Score test

Likelihood Ration test

est statistics ust in case... LR

Example

inculation.

Define the Hessian-based and outer-product versions:

$$H(\theta) = -\mathbb{E}\left[\nabla^2_{\theta\theta^{\top}}\ell(X_i,\theta)\right], \qquad J(\theta) = \mathbb{E}\left[\nabla_{\theta}\ell(X_i,\theta)\nabla_{\theta}\ell(X_i,\theta)^{\top}\right].$$

• Information Matrix Equality: Under correct model specification,

$$J(\theta) = H(\theta).$$

- Consequences:
 - 1 The Score test statistic simplifies to

$$\zeta_n^S = n \, s(\hat{\theta}^0)^\top \left[\hat{H}(\hat{\theta}^0) \right]^{-1} s(\hat{\theta}^0).$$

- 2 This ensures the asymptotic equivalence of the Wald, Score, and LR tests.
- If the model is misspecified: $J(\theta) \neq H(\theta)$, and robust (sandwich) variance estimation is required.

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Introduction to Large Sample Test

3 tests

Wald test

Score test

Test statistics

xample

Likelihood Ration test

 \Rightarrow We want to test whether $M_n(\hat{\theta}) - M_n(\hat{\theta}^0)$ is close to zero or not. Assume $J(\theta) = H(\theta)$.

Theorem

Under H_0 , the test statistic, $\zeta_n^R = 2n(M_n(\hat{\theta} - M_n(\hat{\theta}^0)))$. satisfies:

$$\zeta_n^R = \zeta_n^W + o_p(1) = \zeta_n^S + o_p(1)$$

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Likelihood Ration test

Test statistics

Difine:

- $M_n(\hat{ heta})$: the value of the maximized UNRESTRICTED objective function.
- $M_n(\hat{ heta^0})$: the value of the maximized RESTRICTED objective function.
- $\bullet \ H(\theta) \colon \operatorname{Hessian \ matrix,} \ H(\theta) = -\mathbb{E} \big[\nabla^2_{\theta\theta^\top} \ell(X_i,\theta) \big].$
- $J(\theta)$: outer-product of the score, $J(\theta) = \mathbb{E}[\nabla_{\theta} \ell(X_i, \theta) \nabla_{\theta} \ell(X_i, \theta)^{\top}].$
- $r(\cdot)$: restriction function, $r(\theta) = 0$ under H_0 .
- n: number of observations.

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Framework

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Vald test

Wald test

Likelihood Ration test

est statistics

Evample

xample

$$\zeta_n^R = 2n \left(M_n(\hat{\theta}) - M_n(\hat{\theta}^0) \right) \xrightarrow[n \to \infty]{d} \chi^2(L)$$

Score:

$$\zeta_n^S = n \, s(\widehat{\theta^0})^\top \, \hat{H}^{-1}(\widehat{\theta^0}) \, s(\widehat{\theta^0}) \xrightarrow[n \to \infty]{d} \chi^2(L),$$

where $s(\theta) = \nabla_{\theta} M_n(\theta)$ is the score vector.

• Wald:

$$\zeta_n^W = n \, r(\hat{\theta})^\top \Sigma_W^{-1}(\hat{\theta}) r(\hat{\theta}) \xrightarrow[n \to \infty]{d} \chi^2(L),$$

$$\Sigma_W(\hat{\theta}) = (\nabla_{\theta} r(\hat{\theta}))^{\top} \hat{H}^{-1}(\hat{\theta}) \hat{J}(\hat{\theta}) \hat{H}^{-1}(\hat{\theta}) (\nabla_{\theta} r(\hat{\theta})).$$

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Introduction to Large Sample Test

Framework

Vald test

Score test

Test statistics

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Why the Likelihood Ratio Test is χ^2 -distributed

• Consider the Likelihood Ratio (LR) statistic:

$$\zeta_n^R = 2[\ell(\hat{\theta}) - \ell(\hat{\theta}^0)],$$

where $\hat{\theta}$ is the unrestricted MLE and $\hat{\theta}^0$ the restricted MLE.

• Taylor expansion around the restricted MLE:

$$\ell(\hat{\theta}) \approx \ell(\hat{\theta}^0) + (\hat{\theta} - \hat{\theta}^0)^{\top} s(\hat{\theta}^0) + \frac{1}{2} (\hat{\theta} - \hat{\theta}^0)^{\top} H(\hat{\theta}^0) (\hat{\theta} - \hat{\theta}^0),$$

where $s(\hat{ heta}^0) =
abla_{ heta} \ell(\hat{ heta}^0)$ and $H(\hat{ heta}^0)$ is the Hessian.

• At the restricted MLE, $s(\hat{\theta}^0)=0$, so

$$\ell(\hat{\theta}) - \ell(\hat{\theta}^0) \approx \frac{1}{2} (\hat{\theta} - \hat{\theta}^0)^{\top} H(\hat{\theta}^0) (\hat{\theta} - \hat{\theta}^0).$$

• Multiplying by 2 cancels the $\frac{1}{2}$ in the quadratic form, yielding

$$\zeta_n^R \approx (\hat{\theta} - \hat{\theta}^0)^\top H(\hat{\theta}^0)(\hat{\theta} - \hat{\theta}^0),$$

which is asymptotically a sum of squares of normal variables $\Rightarrow \chi^2$.

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ntroduction to

Framework

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ald test

Test statistics

Just in case... LR

imulation

1 Introduction to Large Sample Test

- 2 Frameworl
- 3 tests

Score test
Likelihood Ration test
Test statistics

Just in case... LF

4 Example

5 Simulation Experiment

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Introduction to Large Sample Test

ramework

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Vald test

Vald test core test

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Example

imulation

Wald Test Example 1

Let $\theta \in \mathbb{R}^d$ and consider the null hypothesis:

$$H_0: \theta_j = 0$$
 (the *j*th element of the parameter vector is 0).

The restriction function is

$$r: \mathbb{R}^d \to \mathbb{R}, \quad r(\theta) = \theta_j.$$

For the Wald test, the Jacobian is

$$(\nabla_{\theta} r(\theta))^{\top} = (0, \dots, 0, 1, 0, \dots, 0),$$

with 1 in the jth position.

The matrix $\Sigma_W(\theta)$ reduces to the scalar $\sigma_i^2(\theta)$, which is the jth diagonal element of

$$\Sigma(\theta) = H^{-1}(\theta)J(\theta)H^{-1}(\theta).$$

Hence, the Wald statistic is

$$\zeta_n^W = n \frac{\widehat{\theta}_j^2}{\sigma_i^2(\theta)},$$

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Example

Wald Test Example 2

$$\ell(y_i, X_i, \theta) = (Y_i - \alpha - \mu \exp(X_i \beta))^2.$$

$$\beta \in \mathbb{R}^{d-2}, \theta = (\alpha, \mu, \beta^{\top})^{\top} \in \mathbb{R}^d.$$

$$H_0: \beta_{0,1} = \beta_{0,2}^3, \ \beta_{0,4} = 5\beta_{0,5}^2.$$

The restriction function is $r: \mathbb{R}^d \to \mathbb{R}^2$ with:

$$r(\theta_0) = \begin{pmatrix} r_1(\theta_0) \\ r_2(\theta_0) \end{pmatrix} = \begin{pmatrix} \beta_{0,1} - \beta_{0,2}^3 \\ \beta_{0,4} - 5\beta_{0,5}^2 \end{pmatrix}$$

The Jacobian becomes:

$$(\nabla_t hetar(theta))^{\top} = \begin{pmatrix} 0 & 0 & 1 & -3\beta_2^2 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 1 & -10\beta_5 & 0 & \cdots & 0 \end{pmatrix}$$

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Example

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Introduction to Large Sample Test

Framework

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Wald test

elihood Ration test

est statistics

ust in case... LR

Example

Simulation

where $\Sigma_W(\hat{\theta}) = (\nabla_{\theta} r(\hat{\theta}))^{\top} \hat{H}^{-1}(\theta) \hat{J}(\theta) \hat{H}^{-1}(\theta) (\nabla_{\theta} r(\hat{\theta})).$

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6 Simulation Experiment

Simulation **Experiment**

Simulation Experiment

Data generating process:

$$X_t = \omega + \beta_1 X_{t-1} + \beta_2 X_{t-2} + u_t, \qquad t = 3, \dots, T,$$

where $u_t \sim N(0, \sigma_u^2)$.

Set the true parameters as:

$$\omega = 0.001, \quad \beta_1 = 0.7, \quad \beta_2 = 0.2, \quad \sigma_u^2 = 0.05.$$

The initial values are drawn as $X_1, X_2 \sim N(0, \sigma_u^2)$, and we set T = 10000. The (negative log-likelihood) loss function is:

$$M_n(\theta) = \frac{1}{2n} \sum_{t=1}^{T} \left\{ \log(2\pi\sigma_u^2) + \frac{\left(X_t - \omega - \beta_1 X_{t-1} - \beta_2 X_{t-2}\right)^2}{\sigma_u^2} \right\}.$$

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Simulation Experiment

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Introduction to Large Sample Test

Framework

3 tests

Wald test

Score test

lihood Ration test

Just in case... LR

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Example

Simulation Experiment

 $\theta = (\omega, \beta_1, \beta_2, \sigma_u^2)$

$H_0:\beta_2=0$

Simulation Experiment: R Code and Results

Output

```
=== 自作計算 ===
```

LR test statistic: 461.5066 Wald test statistic: 472.1822 Score test statistic: 451.017

```
=== パッケージ版 ===
```

Likelihood ratio test

Model 1: Y ~ X_lag1

Model 2: Y ~ X_lag1 + X_lag2
#Df LogLik Df Chisq Pr(>Chisq)

1 3 573.23

2 4 803.98 1 461.51 < 2.2e-16 ***

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Framework

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ald test

Wald test Score test

kelihood Ration test

st in case... LR

xample

Simulation Experiment

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Output
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Wald test

Model 1: Y ~ X_lag1

 $\label{eq:model 2: Y ~ X_lag1 + X_lag2} \\ \text{Model 2: Y ~ X_lag1 + X_lag2}$

Res.Df Df Chisq Pr(>Chisq)

1 9996

2 9995 1 472.18 < 2.2e-16 ***

Linear hypothesis test:

 $X_{lag2} = 0$

Model 1: restricted model

Model 2: Y ~ X_lag1 + X_lag2

Res.Df RSS Df Sum of Sq Chisq Pr(>Chisq)

1 9996 521.96

2 9995 498.42 1 23.546 472.18 < 2.2e-16 ***

T-2がデータの数なのに留意。

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tests

ald test

lihood Ration test

st in case... LR

ample

Simulation