Package ‘IGPFrailty’

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Type Package

Title Inverse Gaussian Process Degradation Models with Frailty

Version 0.1.0

Description Maximum likelihood estimation and reliability inference for Inverse Gaussian Process (IGP) degradation models with gamma and inverse Gaussian frailty terms, as formulated by Morita et al. (2021) <doi:10.1002/qre.2762>. Classical IGP degradation models are described in Wasan (1968) and Meeker and Escobar (1998, ISBN:978-0471143284). The package provides tools for calculating lifetime cumulative distribution functions, probability density functions, lifetime quantiles with confidence intervals, posterior individual unit frailties, and goodness-of-fit diagnostics.

License GPL (>= 3)

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Contents

ad_test_ig . . . 2
crack . . . 3
d_ig . . . 4
igp_fit . . . 6
individual_frailty . . . 8
laser . . . 9
lifetime_dist . . . 10
print.igp_fit . . . 12
sim_igp . . . 14

Index **16**

`ad_test_ig` *Goodness-of-Fit and Diagnostic Tests for Inverse Gaussian Process Models*

Description

Evaluates the Anderson-Darling goodness-of-fit test for Inverse Gaussian degradation increments and computes Likelihood Ratio Tests (LRT) for nested frailty models.

Usage

```
ad_test_ig(dy, dg, eta)

lr_test(model0, model1)
```

Arguments

`dy`	Numeric vector of observed degradation increments.
`dg`	Numeric vector of evaluated mean function increments $\Delta g_\theta(t)$.
`eta`	Precision/scale parameter $\eta > 0$.
`model0`, `model1`	Fitted objects of class `"igp_fit"` representing the null (nested) and alternative models.

Details

The Anderson-Darling statistic A^2 tests the null hypothesis that the observed degradation increments follow the specified Inverse Gaussian distribution:

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\log(u_{(i)}) + \log(1 - u_{(n-i+1)})\right]$$

where $u_{(i)}$ are the sorted probability integral transformed residuals $u_i = F_{\text{IG}}(\Delta y_i; \Delta g_i, \eta(\Delta g_i)^2)$.

The Likelihood Ratio Test statistic compares nested models (e.g., Classical IGP vs IGP-Gamma):

$$\text{LRT} = 2(\log L_1 - \log L_0) \sim \chi^2(df)$$

Value

ad_test_ig returns an object of class "ad_test_ig" containing:

statistic	The computed Anderson-Darling statistic A^2.
p_value	Asymptotic p-value for the test.
n	Sample size.

lr_test returns an object of class "lr_test" containing:

statistic	The LRT test statistic.
df	Degrees of freedom difference.
p_value	P-value based on the chi-squared distribution.
model0_loglik, model1_loglik	Log-likelihoods of both models.

References

Anderson, T. W., & Darling, D. A. (1954). A test of goodness of fit. *Journal of the American Statistical Association*, 49(268), 765-769. doi:10.1080/01621459.1954.10501232.

See Also

igp_fit

Examples

```
data(laser)
fit_none <- igp_fit(laser, time_col = "t", deg_col = "increase",
                    unit_col = "unit", frailty = "none")
fit_gamma <- igp_fit(laser, time_col = "t", deg_col = "increase",
                     unit_col = "unit", frailty = "gamma")

# LRT comparing IGP vs IGP-Gamma
lr_test(fit_none, fit_gamma)
```

---

crack *Fatigue Crack Growth Degradation Dataset*

Description

Experimental fatigue crack length measurements on 21 alloy specimens subjected to cyclic stress testing up to 0.12 million cycles (120 thousand cycles).

Usage

```
crack
```

Format

A data frame with 262 rows and 6 variables:

specimen Integer specimen identifier (1 to 21).

megacycles Inspection time in millions of cycles (0.00 to 0.12).

cycles Inspection time in cycles (0 to 120,000).

t Inspection time in thousands of cycles (0 to 120).

inches Crack length measurement in inches (initial crack 0.90 inches, failure at 1.60 inches).

deg Transformed cumulative degradation $D^*(t) = \log(D(t)/0.90)$, with failure threshold $\rho = 0.5754$.

Source

Lu, C. J., & Meeker, W. Q. (1993). Using degradation measures to estimate a time-to-failure distribution. *Technometrics*, 35(2), 161-174. doi:10.1080/00401706.1993.10485038.

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

Examples

```
data(crack)
head(crack)
```

---

d_ig *Inverse Gaussian Distribution Functions*

Description

Density, distribution function, quantile function, and random generation for the Inverse Gaussian (Wald) distribution with mean `mu` and shape/scale parameter `lambda`.

Usage

```
d_ig(x, mu = 1, lambda = 1, log = FALSE)

p_ig(q, mu = 1, lambda = 1, lower.tail = TRUE, log.p = FALSE)

q_ig(p, mu = 1, lambda = 1, lower.tail = TRUE, log.p = FALSE)

r_ig(n, mu = 1, lambda = 1)
```

Arguments

`x, q`	Numeric vector of quantiles. Must be positive.
`mu`	Mean parameter. Must be strictly positive. Default is 1.
`lambda`	Shape parameter. Must be strictly positive. Default is 1.
`log, log.p`	Logical; if `TRUE`, probabilities/densities are returned on the log scale. Default is `FALSE`.
`lower.tail`	Logical; if `TRUE` (default), probabilities are $P[X \le x]$, otherwise $P[X > x]$.
`p`	Numeric vector of probabilities (between 0 and 1).
`n`	Number of observations to generate. Must be a single positive integer.

Details

The probability density function of the Inverse Gaussian distribution is:

$$f(x; \mu, \lambda) = \sqrt{\frac{\lambda}{2\pi x^3}} \exp\left(-\frac{\lambda(x-\mu)^2}{2\mu^2 x}\right), \quad x > 0$$

The cumulative distribution function is evaluated using:

$$F(x; \mu, \lambda) = \Phi\left(\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} - 1\right)\right) + \exp\left(\frac{2\lambda}{\mu}\right)\Phi\left(-\sqrt{\frac{\lambda}{x}}\left(\frac{x}{\mu} + 1\right)\right)$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function.

Value

`d_ig` returns the density, `p_ig` returns the distribution function, `q_ig` returns the quantile function, and `r_ig` returns a vector of random variates of length `n`.

References

Wasan, M. T. (1968). On an inverse Gaussian process. *Scandinavian Actuarial Journal*, 1968(1-2), 69-96.

See Also

`igp_fit`, `sim_igp`

Examples

```
# Density and CDF
d_ig(1.5, mu = 2, lambda = 5)
p_ig(1.5, mu = 2, lambda = 5)

# Quantiles and random generation
q_ig(0.5, mu = 2, lambda = 5)
set.seed(123)
r_ig(5, mu = 2, lambda = 5)
```

igp_fit *Fit Inverse Gaussian Process Degradation Models with Frailty*

Description

Fits an Inverse Gaussian Process (IGP) degradation model to longitudinal or repeated-measures degradation data, with optional gamma or inverse Gaussian frailty to account for unobserved unit-to-unit heterogeneity.

Usage

```
igp_fit(
  data,
  time_col = "t",
  deg_col = "increase",
  unit_col = "unit",
  frailty = c("none", "gamma", "ig"),
  mean_fun = "linear",
  start = NULL,
  method = "BFGS",
  control = list()
)
```

Arguments

`data`	A data frame containing degradation measurements across units over time.
`time_col`	Character string specifying the name of the column in `data` containing inspection times. Default is `"t"`.
`deg_col`	Character string specifying the name of the column in `data` containing cumulative degradation values. Default is `"increase"`.
`unit_col`	Character string specifying the name of the column in `data` containing unit/specimen IDs. Default is `"unit"`.
`frailty`	Character string specifying the frailty distribution. Options are `"none"` for classical IGP, `"gamma"` for IGP with gamma frailty, or `"ig"` for IGP with inverse Gaussian frailty. Default is `"none"`.
`mean_fun`	Character string or custom function specifying the mean degradation function $g_\theta(t)$. Options are `"linear"` for $g_\theta(t) = \theta t$ (default), `"power"` for $g_\theta(t) = \theta_1 t^{\theta_2}$, `"exponential"` for $g_\theta(t) = \exp(\theta t) - 1$, or a user-defined function of the form `function(t, theta)`.
`start`	Optional numeric vector of initial parameter values. If `NULL` (default), automatic heuristic starting values are computed.
`method`	Character string specifying the optimization method to pass to `optim`. Default is `"BFGS"`.
`control`	Optional list of control parameters forwarded to `optim`.

Details

In reliability analysis, degradation paths of high-reliability components are often monitored over time. The classical Inverse Gaussian Process (IGP) models the degradation increments $\Delta D(t) = D(t + \Delta t) - D(t)$ as independent Inverse Gaussian random variables:

$$\Delta D(t) \sim \text{IG}(\Delta g_\theta(t), \eta(\Delta g_\theta(t))^2)$$

where $g_\theta(t)$ is a monotone increasing mean function and $\eta > 0$ is the precision/scale parameter.

When experimental units exhibit unobserved heterogeneity, a multiplicative frailty variable $z_i > 0$ modifies the conditional hazard of unit i:

$$h_i(y \mid z_i) = \frac{1}{z_i} h_{\text{IGP}}(y)$$

Under the **IGP-Gamma** model, $z_i \sim \text{Gamma}(1/\xi, \xi)$ with mean 1 and variance $\xi > 0$. Under the **IGP-IG** model, $z_i \sim \text{IG}(1, 1/\xi)$ with mean 1 and variance $\xi > 0$.

Parameters are estimated via Maximum Likelihood Estimation (MLE) in unconstrained log-parameter space $(\log\theta, \log\eta, \log\xi)$, guaranteeing strictly positive estimates. Standard errors and covariance matrices are derived using the Delta method and numerical inversion of the Hessian matrix.

Value

An object of class "igp_fit" containing:

coefficients	Named numeric vector of estimated parameters (e.g., theta, eta, and xi if frailty is present).
std_errors	Named numeric vector of asymptotic standard errors.
vcov	Variance-covariance matrix of parameter estimates.
loglik	Maximised log-likelihood value.
aic	Akaike Information Criterion (AIC).
bic	Bayesian Information Criterion (BIC).
frailty	The frailty distribution used ("none", "gamma", or "ig").
mean_fun_name	Name/type of mean function.
mean_fun	The mean function evaluated.
n_units	Number of unique experimental units.
n_obs	Total number of degradation increment observations.
convergence	Convergence code returned by optim (0 indicates successful convergence).
unit_data	List of per-unit sorted increments and inspection times.
data	Original data frame supplied.
call	The matched call.

References

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

Meeker, W. Q., & Escobar, L. A. (1998). *Statistical Methods for Reliability Data*. John Wiley & Sons.

See Also

individual_frailty, lifetime_dist, lr_test, sim_igp

Examples

```
# Fit Classical IGP, IGP-Gamma, and IGP-IG to laser degradation data
data(laser)
fit_none  <- igp_fit(laser, time_col = "t", deg_col = "increase",
                     unit_col = "unit", frailty = "none")
fit_gamma <- igp_fit(laser, time_col = "t", deg_col = "increase",
                     unit_col = "unit", frailty = "gamma")
fit_ig    <- igp_fit(laser, time_col = "t", deg_col = "increase",
                     unit_col = "unit", frailty = "ig")

# Summary comparison
summary(fit_none)
summary(fit_gamma)
summary(fit_ig)
```

`individual_frailty` *Individual Frailty Estimation for Degradation Units*

Description

Computes empirical Bayes / posterior individual frailty estimates $E[z_i \mid \text{Data}_i]$ and posterior variances $\text{Var}(z_i \mid \text{Data}_i)$ for each experimental unit.

Usage

```
individual_frailty(object, conf_level = 0.95)
```

Arguments

`object`	An object of class `"igp_fit"` fitted with frailty (`"gamma"` or `"ig"`).
`conf_level`	Nominal confidence level for posterior frailty intervals. Default is `0.95`.

Details

Under the **IGP-Gamma** model, the posterior distribution of the frailty variable given the degradation path is:

$$\pi(z_i \mid \mathbf{y}_i) \propto z_i^{1/\xi - n_i - 1} \exp\left(-\frac{z_i}{\xi} - \frac{S_{Hi}}{z_i}\right)$$

which corresponds to a Generalized Inverse Gaussian (GIG) distribution.

Under the **IGP-IG** model, the posterior distribution is:

$$\pi(z_i \mid \mathbf{y}_i) \propto z_i^{-1.5 - n_i} \exp\left(-\frac{(z_i - 1)^2}{2\xi z_i} - \frac{S_{Hi}}{z_i}\right)$$

also belonging to the GIG family.

Posterior moments are evaluated analytically using modified Bessel functions of the second kind $K_\nu(\cdot)$. Units with higher $\hat{z}_i$ exhibit higher degradation rates and greater failure proneness.

Value

An object of class `"individual_frailty"` containing:

`estimates`	Data frame with columns: `unit`, `n_obs`, `cum_deg`, `E_z` (posterior mean), `Var_z`, `SD_z`, `CI_Lower`, `CI_Upper`, and `fragility_rank`.
`frailty_type`	Type of frailty distribution.
`most_fragile`	Subset of top fragile units.
`least_fragile`	Subset of least fragile units.
`conf_level`	Nominal confidence level.

References

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

See Also

`igp_fit`, `lifetime_dist`

Examples

```
data(laser)
fit_gam <- igp_fit(laser, time_col = "t", deg_col = "increase",
                   unit_col = "unit", frailty = "gamma")
frail_est <- individual_frailty(fit_gam)
print(frail_est)
```

`laser` *GaAs Laser Degradation Dataset*

Description

Repeated-measures degradation data on 15 Gallium Arsenide (GaAs) laser devices tested at 80 degrees Celsius over 4,000 hours of operation with 16 equidistant inspection intervals.

Usage

```
laser
```

Format

A data frame with 255 rows and 5 variables:

unit Integer unit identifier (1 to 15).

unit_id Original unit ID code (101 to 115).

hours Inspection time in hours (0, 250, 500, ..., 4000).

t Inspection time in thousands of hours (0.0 to 4.0).

increase Percentage increase in operating current (%), with failure defined at 10%.

Source

Meeker, W. Q., & Escobar, L. A. (1998). *Statistical Methods for Reliability Data*. John Wiley & Sons.

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

Examples

```
data(laser)
head(laser)
```

`lifetime_dist` *Lifetime Distribution and Quantile Estimation for IGP Degradation Models*

Description

Computes the implied lifetime cumulative distribution function (CDF), probability density function (PDF), survival function, and quantiles with asymptotic confidence intervals for a predefined failure threshold ρ.

Usage

```
lifetime_dist(
  object,
  threshold,
  times = NULL,
  probs = c(0.01, 0.05, 0.1, 0.5, 0.8),
  conf_level = 0.95
)
```

Arguments

`object`	An object of class `"igp_fit"`.
`threshold`	Numeric failure threshold $\rho > 0$ at which a unit is declared failed.
`times`	Optional numeric vector of evaluation time points. If `NULL`, an automatic sequence spanning the lifetime domain is generated.
`probs`	Numeric vector of quantile probabilities. Default is `c(0.01, 0.05, 0.1, 0.5, 0.8)`.
`conf_level`	Nominal confidence level for quantile asymptotic confidence intervals. Default is `0.95`.

Details

In threshold degradation models, the soft failure time T is defined as:

$$T = \inf\{t \geq 0 : D(t) \geq \rho\}$$

The lifetime CDF $F_T(t)$ is the probability that cumulative degradation exceeds ρ:

$$F_T(t) = P(D(t) \geq \rho) = 1 - F(\rho \mid g_\theta(t), \eta, \xi) = R(\rho \mid g_\theta(t), \eta, \xi)$$

For the **classical IGP** model:

$$F_{T,\text{IGP}}(t) = \Phi\left(-\sqrt{\frac{\eta}{\rho}}(\rho - g_\theta(t))\right) - \exp(2\eta g_\theta(t))\Phi\left(-\sqrt{\frac{\eta}{\rho}}(\rho + g_\theta(t))\right)$$

For the **IGP-Gamma** model:

$$F_{T,\text{Gamma}}(t) = \frac{2\xi^{-1/(2\xi)}(H_{\text{IGP}}(\rho))^{1/(2\xi)}K_{1/\xi}\left(2\sqrt{\frac{H_{\text{IGP}}(\rho)}{\xi}}\right)}{\Gamma(1/\xi)}$$

For the **IGP-IG** model:

$$F_{T,\text{IG}}(t) = \frac{\exp\left(-\frac{\sqrt{1+2\xi H_{\text{IGP}}(\rho)}-1}{\xi}\right)}{\sqrt{1+2\xi H_{\text{IGP}}(\rho)}}$$

where $H_{\text{IGP}}(\rho) = -\log R_{\text{IGP}}(\rho \mid g_\theta(t), \eta)$.

Quantiles t_p are computed by numerical root finding on $F_T(t_p) = p$. Asymptotic standard errors for $\hat{t}_p$ are obtained via the Delta method using the estimated variance-covariance matrix of parameter estimates.

Value

An object of class `"lifetime_dist"` containing:

`threshold`	The specified failure threshold ρ.
`quantiles`	Data frame containing estimated quantiles `Estimate`, `Std. Error`, `CI Lower`, and `CI Upper`.
`curve`	Data frame with evaluation grid: `t`, `CDF`, `PDF`, `Survival`, and `Hazard`.
`conf_level`	Nominal confidence level.

References

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

See Also

igp_fit, individual_frailty

Examples

```
data(laser)
fit_gam <- igp_fit(laser, time_col = "t", deg_col = "increase",
                   unit_col = "unit", frailty = "gamma")
lt <- lifetime_dist(fit_gam, threshold = 10, probs = c(0.01, 0.05, 0.1, 0.5, 0.8))
print(lt)
```

`print.igp_fit` *Methods for Inverse Gaussian Process Fit Objects*

Description

Standard S3 methods for objects of class "igp_fit": print, summary, coef, vcov, logLik, AIC, BIC, confint, predict, and plot.

Usage

```
## S3 method for class 'igp_fit'
print(x, digits = 4, ...)

## S3 method for class 'igp_fit'
summary(object, conf_level = 0.95, ...)

## S3 method for class 'summary_igp_fit'
print(x, digits = 4, ...)

## S3 method for class 'igp_fit'
coef(object, ...)

## S3 method for class 'igp_fit'
vcov(object, ...)

## S3 method for class 'igp_fit'
logLik(object, ...)

## S3 method for class 'igp_fit'
```

```
AIC(object, ..., k = 2)

## S3 method for class 'igp_fit'
BIC(object, ...)

## S3 method for class 'igp_fit'
confint(object, parm, level = 0.95, ...)

## S3 method for class 'igp_fit'
predict(
  object,
  newdata = NULL,
  threshold = NULL,
  times = NULL,
  probs = c(0.01, 0.05, 0.1, 0.5, 0.8),
  type = c("lifetime", "frailty", "quantiles"),
  ...
)

## S3 method for class 'igp_fit'
plot(
  x,
  type = c("paths", "frailty", "lifetime", "diagnostics", "all"),
  threshold = NULL,
  ...
)
```

Arguments

x, object	An object of class "igp_fit".
digits	Integer indicating the number of decimal places to format. Default is 4.
...	Further arguments passed to or from other methods.
conf_level, level	Nominal confidence level (e.g. 0.95 for 95% confidence intervals). Default is 0.95.
k	Optional numeric penalty per parameter for AIC (default is 2).
parm	Optional vector of numbers or parameter names to compute confidence intervals for.
newdata	Optional new data frame for prediction.
threshold	Failure threshold ρ for lifetime and quantile calculations.
times	Numeric vector of inspection times for lifetime predictions.
probs	Numeric vector of quantile probabilities. Default is c(0.01, 0.05, 0.1, 0.5, 0.8).
type	For predict, one of "lifetime", "frailty", or "quantiles". For plot, one of "paths" (degradation paths), "frailty" (individual frailty barplot), "lifetime" (lifetime PDF and CDF curves), "diagnostics" (P-P and Q-Q plots), or "all".

Value

- `print.igp_fit`: Prints model summary and returns `x` invisibly.
- `summary.igp_fit`: Returns an object of class `"summary_igp_fit"`.
- `coef.igp_fit`: Returns named vector of estimated parameters.
- `vcov.igp_fit`: Returns the variance-covariance matrix.
- `logLik.igp_fit`: Returns log-likelihood with degrees of freedom and observations.
- `AIC.igp_fit`, `BIC.igp_fit`: Return model selection criterion values.
- `confint.igp_fit`: Returns confidence interval matrix.
- `predict.igp_fit`: Returns predicted lifetime distribution, quantiles, or frailties.
- `plot.igp_fit`: Generates base graphics diagnostic and predictive plots.

See Also

`igp_fit`, `individual_frailty`, `lifetime_dist`

Examples

```
data(laser)
fit <- igp_fit(laser, time_col = "t", deg_col = "increase",
               unit_col = "unit", frailty = "gamma")
print(fit)
summary(fit)
coef(fit)
vcov(fit)
logLik(fit)
AIC(fit)
BIC(fit)
confint(fit)
```

---

sim_igp — *Simulation of Inverse Gaussian Process Degradation Paths*

Description

Simulates longitudinal degradation measurements for multiple units under classical IGP, IGP-Gamma frailty, or IGP-IG frailty models.

Usage

```
sim_igp(
  n = 10,
  times = seq(0, 4, by = 0.25),
  theta = 2,
  eta = 15,
```

```
    xi = 0.2,
    frailty = c("none", "gamma", "ig"),
    mean_fun = "linear",
    seed = NULL
  )
```

Arguments

`n`	Integer specifying the number of experimental units to simulate.
`times`	Numeric vector of inspection times (e.g. `seq(0, 4, by = 0.25)`). Must start at 0.
`theta`	Mean parameter $\theta > 0$ (or numeric vector for non-linear mean functions).
`eta`	Precision/scale parameter $\eta > 0$.
`xi`	Frailty variance parameter $\xi > 0$. Ignored if `frailty = "none"`.
`frailty`	Frailty specification: `"none"` (default), `"gamma"`, or `"ig"`.
`mean_fun`	Mean degradation function `"linear"` (default), `"power"`, `"exponential"`, or a custom function.
`seed`	Optional integer random seed for reproducibility.

Value

A data frame containing simulated degradation paths:

unit Integer unit identifier (1 to `n`).

t Inspection time.

increment Simulated degradation increment $\Delta D(t)$.

degradation Simulated cumulative degradation $D(t)$.

frailty_z Realized individual frailty multiplier z_i for unit i.

References

Morita, L. H. M., Tomazella, V. L. D., Balakrishnan, N., Ramos, P. L., Ferreira, P. H., & Louzada, F. (2021). Inverse Gaussian process model with frailty term in reliability analysis. *Quality and Reliability Engineering International*, 37(2), 763-784. doi:10.1002/qre.2762.

See Also

`igp_fit`, `lifetime_dist`

Examples

```
set.seed(42)
sim_data <- sim_igp(n = 5, times = seq(0, 2, by = 0.5), theta = 1.5,
                    eta = 10, xi = 0.3, frailty = "gamma")
head(sim_data)
```

Index

∗ **datasets**
crack, 3
laser, 9

ad_test_ig, 2
AIC.igp_fit *(print.igp_fit)*, 12

BIC.igp_fit *(print.igp_fit)*, 12

coef.igp_fit *(print.igp_fit)*, 12
confint.igp_fit *(print.igp_fit)*, 12
crack, 3

d_ig, 4

igp_fit, *3*, *5*, 6, *9*, *12*, *14, 15*
individual_frailty, *8*, 8, *12*, *14*

laser, 9
lifetime_dist, *8, 9*, 10, *14, 15*
logLik.igp_fit *(print.igp_fit)*, 12
lr_test, *8*
lr_test *(ad_test_ig)*, 2

optim, *6, 7*

p_ig *(d_ig)*, 4
plot.igp_fit *(print.igp_fit)*, 12
predict.igp_fit *(print.igp_fit)*, 12
print.igp_fit, 12
print.summary_igp_fit *(print.igp_fit)*, 12

q_ig *(d_ig)*, 4

r_ig *(d_ig)*, 4

sim_igp, *5*, *8*, 14
summary.igp_fit *(print.igp_fit)*, 12

vcov.igp_fit *(print.igp_fit)*, 12