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Current research is concentrated in several important areas of life testing and reliability which are theoretically challenging as well as directly motivated from potential practical applications to engineering systems. Particular emphasis was placed on the development of procedures that are appropriate for costly experiments involving small sample sizes.

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LIFE TESTING AND RELIABILITY WITH APPLICATION IN ENGINEERING SYSTEMS

Richard A. Johnson and Gouri K. Bhattacharyya

Introduction

Current research is concentrated in several important areas of life testing and reliability which are theoretically challenging as well as directly motivated from potential practical applications to engineering systems. Particular emphasis was placed on the development of procedures that are appropriate for costly experiments involving small sample sizes.

This report provides an outline of our research work during the period 6/15/88 - 6/14/89 and a projection of additional advances to be made during 1989-1990.

1. Nonparametric Inference with Censored Data

One major area of concentration of our research pertains to nonparametric approaches to truncated data problems. An interesting extension of the truncation model states that an object with response x (life length or size) has probability $H(x)$ of being observed. We have a manuscript on distribution-free two sample tests accepted for publication.

Further advances have been made on the construction of confidence intervals for a translation parameter. These overcome a fundamental difficulty due to the fact that if observations are translated beyond the truncation point, they become unobservable and the sample size is decreased.

In the case of randomly censored data, we have uncovered major discrepancies, with respect to approximate normality, of different versions of approximate scores test. We are actively pursuing corrections based on a symmetrized version of the statistics.

2. Life Length Analysis under Parametric Models

The normal and lognormal distributions sometimes serve as models for lifelength or a strength property so it is important to check the model assumptions before making inferences. We have one published paper and two manuscripts accepted.

In another important direction, we are in the process of extending the total-time-on-test statistic to Weibull and other distributions.

3. Models and Inference Procedures for System Reliability

The increased complexity of system structures developed by present day technology emphasizes the need for building new models for system reliability by incorporating subsystem

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failure mechanisms, component wearout and possible impediments due to environmental stresses.

When evaluating a system reliability, the component or subsystem reliabilities are often assumed to be independent for the sake of mathematical simplicity but this assumption is questionable in many practical situations. Concerned with the various physical ways in which a dependence could arise, we have recently advanced several bivariate extensions of the Weibull distribution. Two other manuscripts have been submitted. One deals with the derivation of some exact inference procedures as well as their large sample properties under a bivariate exponential model of Gumbel; and the other derives procedures for type II censored data which are procured partly from components tests and partly from system tests.

Another direction of current activity concerns the formulation of models that incorporate covariates into the stress-strength reliability framework. We have published a chapter on stress-strength modeling and a paper that advances a Bayesian approach to inference procedures in this setting.

4. Monitoring Quality for Strength Variables

When tests are conducted on strength variables, the unit is loaded to failure. Each unit tested is destroyed. However, stiffness can be measured without damage to the specimen. In the context of screening for strength, specimens could be classified on the basis of the covariate stiffness. A current Ph. D. student has obtained new optimal screening rules within the framework of a decision theory setting. These results are now being extended to the general classification problem. The properties of these procedures are under investigation.

Another Ph. D. student, is continuing to make progress on developing statistical designs for proof loading schemes and nonparametric procedures for estimating the correlation between two destructively tested strength properties. Under this approach, a specimen is loaded to a specified proof load. If it breaks then another specimen is selected. If it survives then it is broken in the second failure mode. Various modifications of the procedure are under consideration. Properties of the statistical procedures are currently being determined.

5. Design and Analysis of Accelerated Life Tests

With accelerated life test(ALT) , the experimental units are subjected to higher stress conditions than in normal use in order that more failure data can be procured in a limited time.

Also, instead of holding the stress at a constant level throughout the life of a test unit, a commonly used engineering practice, called step-stress ALT, is to change the stress setting at specified times on the surviving units. Our recent research in the area of ALT has been targeted to model formulation and development of inference procedures for step-stress ALT experiments with attention to the design of stress changes. We have proposed a tampered failure-rate model which, in the parametric setting of a Weibull family for the life distribution under a constant stress, has considerable analytical advantage over the commonly used cumulative-exposure model. Some basic inference procedures are developed and an extension of the model to include a regression structure is introduced. the latter is now under investigation.

Another direction of our current research is modeling step-stress ALT from the viewpoint of cumulative damage in line with our previous formulation of an inverse Gaussian regression model which turned out to be very effective in analyzing constant-stress ALT data. Assuming



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the damage growth to follow a Wiener process with a positive drift that depends on the stress, we have derived a life-model for the simple step-stress ALT. Statistical properties of this model as well as its application and extension are currently being studied.

ALT experiments are often conducted first on the components and then on the assembled system. We need to combine the failure information obtained from component-level and system-level testings in the framework of a statistical model for an assessment of the system life under normal use condition stress. Work with some parametric models, including the possibility of dependence of the components in a series system, is in progress.

6. Reliability Growth Models.

Our most exciting results are directly applicable to estimating the reliability for single-mission systems undergoing development and improvement. Our research focuses on the development of parameter estimation and confidence procedures for a discrete reliability growth model that is currently under consideration by contractors for single-mission systems. Three papers have been accepted for publication that detail the unusual large sample theory and present large sample confidence intervals for the parameters and last stage reliability.

Finkelstein formulated a "logarithmic growth model" in analogy with a continuous-time growth model based on a nonhomogeneous Poisson process, and proposed the continuous analog estimators (CAE's). We have established the asymptotic properties of the CAE's and developed large-sample confidence procedures for the model parameters as well as the system reliability. This discrete growth model poses a non-standard situation in regard to the asymptotic theory of maximum likelihood estimators (MLE's). By developing an appropriate method we have obtained the large-sample properties of the MLE's and CAE's in a common setting and established their equivalence. Another important testing scheme concerns inverse binomial sampling. We are now studying a discrete growth model that is relevant to the inverse binomial testing scheme. In addition to investigating the properties of the MLE's, we hope to develop simpler estimators and associated confidence procedures.

Ph. D. Thesis Supervision.

One student completed his thesis

Bivariate Weibull Models and Inferences Based on Life Test of Systems and Components.
(July 1988)

Two thesis students are currently being supervised. Their topics are:

Nonparametric Approaches for Estimating the Correlation Between Two Destructively Tested Strength Properties.

Bayesian Methods for Classification and Screening for Quality.

Two additional students are starting supervised research in the area of reliability growth models.

PUBLICATIONS AND TECHNICAL REPORTS

Stress-Strength Reliability Models(1988). *Encyclopedia of Statistics*, Ed. C. R. Rao and P. R. Krishnaiah. Chapter 3, 7, 27-54, North Holland.

Tables and Large-sample Distribution Theory for Censored-Data Correlation Statistics for Testing Normality(1988). *J. Amer. Statist. Assoc.* **83**, 1192 - 1197.

The Large Sample Distribution of a Quadratic Form with Application to Goodness-of-Fit(1989) *Comm. Statist.* **17** , 4011-4024.

Properties of Continuous Analog Estimators for a Discrete Reliability Growth Model(1989). To appear in *I.E.E.E. Tran. Reliability*.

Two-Sample Rank Tests Under a Random Truncation Model (1989). To appear in *Statist. Probability Letters*.

Confidence Estimation with Discrete Reliability Growth Models(1989). To appear *J. Statist. Planning and Inference.*(*Proceedings on International Reliability conference.*)

Estimation of Parameters in a Discrete Reliability Growth Model and Some Non-Standard Asymptotics(1988). To appear *J. Statist. Planning and Inference.*(*Proceedings on International Reliability conference.*)

A Linear Combination Test for Detecting Serial Correlation in Multivariate Samples(1989). To appear in Conference Proceedings From Dependence and Reliability Conference.

Inference Procedures for a Bivariate Exponential Model of Gumbel based on Life Test of Components and Systems(1989.) Technical Report No. 855, Department of Statistics, University of Wisconsin.

Confidence Limits for Stress-Strength Models with Explanatory Variables (1988). *Technometrics* **30**, 161-168.

Some New Constructions of Bivariate Weibull Models. (1989). To appear in *Ann. Statist. Math.*

The Large Sample Distribution of the Shapiro-Wilk Statistic and it Variations Under Type I and Type II Right Censoring (1989). To appear in *Statist. Probability Letters*.

A Tampered Failure Rate Model for Step-Stress Accelerated Life Tests(1989). *Comm. Statist.-Theory and Methods*, **18**, 1627-1644.

Some Bivariate Extensions of the Weibull Distribution (1988). Technical Report no. 821, Department of Statistics, University of Wisconsin.

Estimation of Parameters in a Discrete Reliability Growth Model and Some Non-Standard Asymptotics(1988). Technical Report no. 834, Department of Statistics, University of Wisconsin. To appear in *Proceedings of Symposium in Memory of R. C. Bose*, New Delhi.

Two-Sample Estimation and Confidence Intervals Under a Truncation Model(1988). Technical Report no. 830, Department of Statistics, University of Wisconsin.

Asymptotic Properties of Estimators in a Binomial Reliability Growth Model and its Continuous-Time Analog (1989). To appear in *J. Statist. Planning and Inference*.(*Proceedings on International Reliability conference*.)

Invited Talks

Lectures on Applied Multivariate Analysis. September 1988, American Statistical Assoc. Alaska Chapter, Anchorage , Alaska.

Seminar Talks at the University of Alaska-Juneau, Arizona, and Virginia.