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EXPERIMENTAL RANDOM FATIGUE IN ELASTIC-PLASTIC RANGE - FIRST OR--ETC(U)
AUG 79 T C HUANG, V K NAGPAL N00014-76-C-0825
UNCLASSIFIED UW/RF-5 NL

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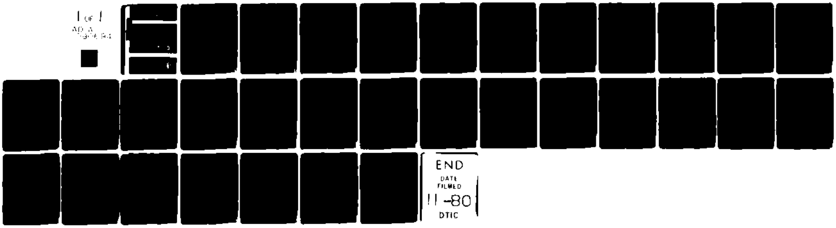

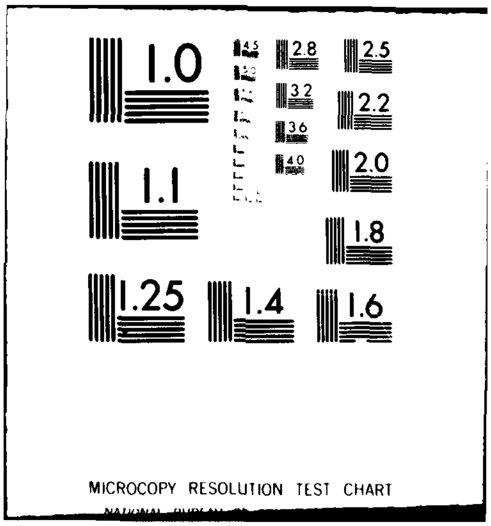
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OFFICE OF NAVAL RESEARCH
Contract No. N00014-76-C-0825
Task No. NR064-576

LEVEL II

EXPERIMENTAL RANDOM FATIGUE IN ELASTIC-PLASTIC RANGE - FIRST ORDER MODELS

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Project: RANDOM FATIGUE
Technical Report No. UW/RF-5
August 1979

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ABSTRACT

An experiment based on 11 probabilistic parameters and experiment design is conducted for fatigue of materials in an elastic-plastic range under random vibrations to develop regression models which will predict the fatigue life. The experiment consisted of a total of 24 tests and is conducted in 3 designs. The response of each test specimen is digitized, recorded, and is fitted with time series models. The time-series model parameters are then used to compute the spectrum and spectral moments from which the magnitude levels of probabilistic parameters are computed and coded. The first-order regression models are developed for each design by regressing the log of fatigue life on the corresponding coded parameters. The tables of the analysis of variance, and of the predicted lives together with residuals and 95% confidence intervals are constructed for each model. From the analysis of variance the F-ratio is computed to check whether the model is acceptable. The first-order model involving all 11 parameters based on 24 tests is considered to be the statistically best one. The methodology of this report is found to be an accurate and reliable approach and is suitable for industrial applications. This method constrasts with the prevailing method which is based on linear damage accumulation and cycle counting, involves a several hundred-percent error as a rule, and is hardly applicable to industrial problems.

INTRODUCTION

The principle of linear damage accumulation based on cycle counting has been consistently found to give unreliable and inaccurate estimates of fatigue life under random vibrations [1-10]. This group of representative references has been discussed in [11].

Recently a new history-dependent, stochastic model of cumulative damage is being developed by Bogdanoff [12-14] by taking a comprehensive view of the entire failure process to improve the predictive accuracy. Another approach, entirely different from all above mentioned approaches, has been developed in [11,15] to predict the fatigue life of materials under random vibrations in the elastic range. The same approach is used now for elastic-plastic range. An experiment program of 24 tests based on 11 probabilistic parameters and experiment design is conducted in 3 designs. For each design the regression models are developed to predict fatigue life under random vibrations. Again, this approach has been found to give very reliable and accurate estimates.

The purpose of this research is to develop a novel methodology for random fatigue based on the probabilistic parameters and experiment design. Therefore, the choice of the specimen materials, types of loadings (axial, shear or bending), and range of parameters is irrelevant and they are arbitrarily chosen.

I. EXPERIMENTS, PARAMETERS, DESIGNS AND MODELS

1. Experiment

The experiment program was conducted with 24 specimens in 3 designs. These specimens were numbered from 25-48 to distinguish them from specimens numbered from 1-24 used in the elastic case [11].

The bending specimen of aluminum alloy 6061-T6 and the experimental set-up described in [11,16,17] were also used for this experiment.

2. Parameters

A typical random response signal in elastic-plastic range which is characterized by 11 probabilistic parameters is given in Fig. 1. They are mean, variance, zero upcrossings, ε_f level upcrossings, ε_y level upcrossings, duration of excursion above zero, duration of excursion above ε_f level, duration of excursion above ε_y level, band width, average amplitude above ε_f level, and average amplitude above ε_y level. In these parameters ε_f represents the strain level corresponding to a material life of 10^7 cycles in the deterministic fatigue tests, and ε_y represents the yield point strain of the material. A mathematical analysis of these 11 probabilistic parameters is given in [18]. Hereafter, these probabilistic parameters will be simply referred to as variables as well.

3. Designs

The first design of the experiment consisted of 10 tests which formed a full factorial design with 2 center points. The second design, a central composite design with 4 center points, was formed by adding 8 more tests to the first design. The third design was formed by adding to the second design random replications of six tests from the second design.

a. Range The first design was based on the three different magnitude levels of the 3 variables, namely, mean, variance and zero upcrossings. Two more levels from each of the 3 variables were added in the second design so that one was lower and the other one higher than the 3 previous levels. In the third design, 6 tests were replicated without introducing new levels of the variables. Thus, the second and the third designs had 5 levels from each of the above 3 variables. The lowest and the highest of the 5 levels represent the lower and upper bounds of the range of variables. The upper bounds of the mean and variance are limited such that the maximum capability of the shaker table displacement is not exceeded. Whenever the displacement exceeds the maximum capability of the shaker, the overtravel limit is reached and the shaker is shut off automatically. Otherwise, the range of the variables can be arbitrarily chosen. The ranges of mean, variance and zero upcrossings based on 5 levels are 241-2657 micro inches/inch, $2.42 \times 10^6 - 4.36 \times 10^6$ (micro inches/inch)^2, and 9.12 - 15.32, respectively.

b. Code The above 3 variables which were controlled in the experiment were coded. The remaining 8 variables which could not be controlled in the experiment were computed from the random response of each test specimen as described in [11]. The variables and the actual levels, and the coded variables and coded levels are shown in Table 1. Tables 2 and 3 show the actual levels of variables and coded levels of coded variables, respectively, of all 11 variables for the 24 tests.

4. Models

The regression models, also referred to as life predicting equations, were obtained for each of the 3 designs as was done in [11]. For the first design only one life predicting equation of 3 variables was obtained. For each of the second and third designs two life predicting equations were obtained, one involves only 3 variables and the other one involves all 11 variables. These equations were obtained by regressing the log of actual life, y, on the corresponding coded variables involved in the model. The models predicted the log of life, $\hat{y}$. The predicted fatigue life, $\hat{T}$, is computed by taking the antilog of $\hat{y}$.

The table of analysis of variance, and the table of predicted lives together with residuals and 95% confidence intervals, are constructed for each model. From the analysis of variance, the F-ratio for each model was computed to determine whether the model is acceptable. The confidence intervals were computed using the standard deviations of $\hat{y}$ and the t values from the t-table with degrees of freedom equal to that of residuals. The distribution of residuals was studied for any pattern or trend present. If the pattern or trend existed, the model was considered to have missed some significant variables. The analysis of 3 designs is given below.

II. FULL FACTORIAL DESIGN WITH TWO CENTER POINTS

The first ten tests from 25-34 of the 24 tests formed a full factorial design with 2 center points. One life predicting equation of three variables is obtained by regressing log of actual life, y, on coded levels of mean, variance and zero upcrossings. These three variables are represented by symbols x_1-x_3. The life predicting equation of all 11 variables could not be obtained.

1. Three Variables

The life predicting equation is obtained as

$$\hat{y} = 3.52 + 0.0538x_1 - 0.341x_2 - 0.0514x_3 \qquad (1)$$

The analysis of variance of equation (1) is given in Table 4. The F-ratio of 4.328 with 3 and 6 degrees of freedom is found. The corresponding F value from the F-table is 4.76 which is greater than the F-ratio of the equation. This implies that the regression is not effective and the model is not acceptable. The residual sum of squares is 0.4862 in comparison to a total of 2.0269, a 32.6%. The other 68.4% of the total sum of squares is due to regression.

This model does not qualify the F-test and may not be acceptable. Nevertheless the predicted lives together with their residuals and 95% confidence intervals are computed as given in Table 5 in order to see how the results of an unacceptable model appear. The confidence intervals are fairly wide because the t value with six degrees of freedom is high. The actual life of the test number 30 only is slightly below the lower limit of the predicted interval.

2. <u>All 11 Variables</u>

The life predicting equation based on all 11 variables could not be obtained because the number of tests in this design is smaller than the variables involved.

III. CENTRAL COMPOSITE DESIGN WITH FOUR CENTER POINTS

The full factorial design is augmented by 8 more tests to form a central composite design with 4 center points resulting in a total of 18 tests. Two life predicting equations are obtained for this design. The first one consists of the same 3 variables, while the second one consists of all 11 variables.

1. Three Variables

The life predicting equation is obtained as

$$\hat{y} = 3.55 + 0.0242x_1 - 0.327x_2 - 0.0597x_3 \qquad (2)$$

The analysis of variance of equation(2) is given in Table 6. The F-ratio of 14.80 with 3 of 14 degrees of freedom is obtained. The corresponding F value from the F-table at 95% significance level is 3.34. The table value of F is smaller than the F-ratio which implies that the regression is effective and the model is acceptable. The residual sum of squares is 0.4862 in comparison to a total of 2.0269, a 24.0%. The other 76.0% of the total sum of squares is due to regression. In this case the sum of squares due zero upcrossings is higher than the sum of squares, due to mean.

The predicted lives together with residuals and 95% confidence interval, are given in Table 7. The confidence intervals are fairly narrow. The actual lives of test numbers 30, 33 and 34 are slightly off from the corresponding predicted interval. The residuals also are relatively large in magnitude. The investigation of this model suggests that more variables which have significant effects on the fatigue life should be introduced.

2. <u>All 11 Variables</u>

The life predicting equation is obtained as

$$\hat{y} = 3.39 - 0.0143x_1 - 0.463x_2 - 0.144x_3 + 0.020x_4 - 0.314x_5 - 0.727x_6 + 0.637x_7 + 0.112x_8 - 0.0103x_9 + 0.101x_{10} - 0.0803x_{11} \quad (3)$$

The analysis of variance of equation (3) is given in Table 8. The F-ratio of 6.036 with 11 and 6 degrees of freedom is obtained for this model. The corresponding F value from the F-table is 2.92 at 95% significance level. The F-ratio is greater than the table value of F which means that the regression is effective and that the model is acceptable. The sum of squares due to residuals is 0.1682 in comparision to a total of 2.0269, a 8.3%. The other 91.7% of the total sum of squares is due to regression. The sum of squares due to 6 of the 11 variables is considered insignificant. These six variables are mean, ε_y level upcrossings, duration of excursion above zero and ε_y levels, band width and average amplitude above ε_f level.

The predicted lives together with residuals and 95% confidence intervals are given in Table 9. The confidence intervals are relatively wide because t value with 6 degrees of freedom associated with the residuals is high. The actual lives of all tests fall within the predicted confidence intervals. The residuals are small in magnitudes.

IV. CENTRAL COMPOSITE DESIGN WITH FOUR CENTER POINTS AND SIX REPLICATIONS

Six more tests are added to the central composite design by randomly replicating six of the 18 tests. Adding these six tests resulted in a total of 24 tests in the design. Two life predicting equations are obtained for this design also, one using 3 variables and another one using all 11 variables. The equations and their analyses are as follows.

1. Three Variables

The life predicting equation is obtained as

$$\hat{y} = 3.56 + 0.0195x_1 - 0.325x_2 - 0.0518x_3 \qquad (4)$$

The analysis of variance of equa[illegible] in Table 10. The F-ratio for the equation above [illegible] 2[illegible] and 20 degrees of freedom which is greater than the co[illegible] value of 3.10 from the F-table at 95% significan[illegible] implies that the regression is effective and the model is acceptable. [illegible] residual sum of squares is 0.6192 in comparison to a total sum of squares of 3.1801, a 20.5%. The other 79.5% of the total is due to regression.

The predicted lives together with residuals and 95% confidence intervals are given in Table 11. The sum of squares due to zero upcrossings in this case is lower than that due to mean. The confidence intervals are comparatively narrow but the actual lives of test nos. 27, 29, 30, 33, 34, 35, 44 and 45 fall out of the corresponding predicted confidence intervals. The residuals are relatively large which imples that some variables which may have significant effects on the fatigue life are missing from the model. The life predicting equation using more variables is discussed below.

2. <u>All 11 Variables</u>

The life predicting equation is obtained as

$$\hat{y} = 3.50 - 0.0105x_1 - 0.398x_2 - 0.0748x_3 + 0.0459x_4 - 0.111x_5 - 0.317x_6 + 0.290x_7 + 0.0091x_8 - 0.0383x_9 + 0.0739x_{10} + 0.0231x_{11} \quad (5)$$

The analysis of variance based on 24 tests of equation (5) is given in Table 12. The F-ratio for the above equation is computed to be 8.812 with 11 and 12 degrees of freedom which is larger than the corresponding F value of 2.73 from the F-table at 95% significance level. The comparison of two F values indicates that the regression is effective and the model is acceptable. The residual sum of squares is 0.3498 in comparison to a total sum of squares of 13.1801, a 11.0%. The other 89% of the total is due to regression, which is significantly high. The six of the 11 variables are considered to be insignificant because they contribute a very low sum of squares to regression. These

6 variables are ε_f level upcrossings, duration of excursion above zero level, duration of excursion above ε_y level, band width, and average amplitudes above ε_f and ε_y levels.

The predicted lives together with residuals and 95% confidence intervals are given in Table 13. The confidence intervals are fairly narrow. Actual lives of all the 24 tests fall within the predicted confidence intervals. The residuals appear to be relatively small and their plot is given in Fig. 2. The plot shows that the residuals are concentrated more on the positive side with fairly small magnitudes.

V. DISCUSSIONS AND CONCLUSIONS

On the basis of the analysis of all models of equations from (1) to (6) it is observed that there are 5 variables which have significant effects on the fatigue life. These 5 significant variables are mean, variance, zero upcrossings, ε_y level upcrossings, and the duration of excursion above ε_f level. The remaining 6 variables are considered to be less significant.

Among the 5 significant variables the variance has the most significant effect. This is obvious because the variance is a measure of square of the amplitude of the strain signal. Consequently a large variance of the signal means large amplitude of the strain. The magnitudes of effects of the remaining four significant variables are low as compared to that of the variance but are not negligible. Variance, ε_y level upcrossings, and duration of excursion above ε_f level show significant effects in all 3 analyses of 10, 18 and 24 tests. The effect of zero upcrossings is found to be pronounced in the analysis of 10 tests and the effect of mean, in the analysis of 24 tests. Nevertheless both mean and zero upcrossings have been included in the list of 5 significant variables.

A comparison of all the first order models investigated in this report with respect to their percent deviations of the predicted lives from the actual ones, and residual sum of squares as percent of the total is given in Table 14. This table shows that the models of all 11 variables for both 18 and 24 tests give a lower percent deviations and a lower percent residual sum of squares in comparison to the model of 3 variables for the same design. Based on 24 tests, the model of equation (5) of all 11 variables is considered the best first order model to predict fatigue life under random vibrations in the elastic-plastic range. The percent deviations of the best model range from -26.0% to 23.2% with an average deviations of 13.4% on the negative side and 8.4% on the positive side. These deviations are negligible as compared to several hundred percent deviations obtained in linear damage accumulation theory.

The lives predicted by the best first order model are expected to be the mean lives of the material for the given levels of variables. The 95% confidence intervals give the range which is expected to include the actual fatigue life for 95% of the tests. The actual life of almost all the tests is greater than the lower level of confidence interval so this level can be considered a conservative estimate of fatigue life.

A few first order and second order models of significant variables will be given in [19].

VI. SUMMARY

(1) An experiment of 24 tests based on 11 variables and experiment design has been performed to predict fatigue life under random vibrations.

(2) The experiment was conducted in 3 designs. For the first design one first order life predicting equation of 3 variables has been developed. For each of the other two designs two first order life predicting equations of 3 and all 11 variables, respectively, have been developed.

(3) The tables of analysis of variance, and of the predicted lives together with residuals and 95% confidence intervals are constructed for each equation.

(4) From the analysis of variance the F-ratio is computed to check whether the regression is effective and the model is acceptable.

(5) Five out of 11 variables have been found to have significant effects on the fatigue life. These 5 variables are mean, variance, zero upcrossings, ε_y level upcrossings and duration of excursion above ε_f level.

(6) The first order life predicting equation of all 11 variables and 24 tests was found to be the statistically best one.

(7) The percent deviations of the predicted lives obtained by the best equation are within a range from -26.0% to 23.2% with an average of 13.4% on the negative side and 8.4% on the positive side. These results are in contrast with those of linear damage accumulation principle.

ACKNOWLEDGMENTS

This research was supported by the U. S. Office of Naval Research under Contract N00014-76-C-0825, Project NR064-576 with the University of Wisconsin-Madison.

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Table 1 Actual Levels, Coded Levels and Coded Variables

No.	Variables	Actual Level Low	Actual Level Center	Actual Level High	Coded Level Low	Coded Level Center	Coded Level High	Coded Variables
1	Mean	400.00	800.00	1600.00	-1	0	+1	x_1
2	Variance	$27.40\text{x}10^5$	$32.80\text{x}10^5$	$38.5\text{x}10^5$	-1	0	+1	x_2
3	Zero Upcrossings	10.50	11.91	13.50	-1	0	+1	x_3
4	ε_f Level Upcrossings	10.50	11.91	13.50	-1	0	+1	x_4
5	ε_y Level Upcrossings	0.25	0.6124	1.50	-1	0	+1	x_5
6	Duration of Excursion Above Zero Level	0.600	0.693	0.800	-1	0	+1	x_6
7	Duration of Excursion Above ε_f Level	0.300	0.387	0.50	-1	0	+1	x_7
8	Duration of Excursion Above ε_y Level	0.003	0.0085	0.01	-1	0	+1	x_8
9	Band Widths	0.96	0.97	0.98	-1	0	+1	x_9
10	Average Amplitude Above ε_f Level	3000.0	3646.0	4000.0	-1	0	+1	x_{10}
11	Average Amplitude Above ε_y Level	5500.0	5979.1	6500.0	-1	0	+1	x_{11}

Table 2 Test Numbers and Actual Levels of 11 Variables

Test No.	Actual Levels of Variables										
	1	2*	3	4	5	6	7	8	9	10	11
25	1601.15	27.7441	10.50	10.44	0.0000	0.82	0.55	0.0000	0.9636	3777.61	0.00
26	410.82	27.2941	13.46	11.05	0.0000	0.82	0.56	0.0000	0.9823	2926.32	0.00
27	1597.20	38.1361	15.32	15.26	0.6739	0.81	0.52	0.0100	0.9778	3802.80	6999.11
28	1605.17	27.3237	12.60	12.54	0.0000	0.83	0.56	0.0000	0.9852	3870.84	0.00
29	410.62	38.4906	11.36	10.24	0.0000	0.57	0.29	0.0000	0.9867	3389 56	0.00
30	403.38	27.4555	10.75	8.77	0.0000	0.61	0.27	0.0000	0.9649	2722.23	0.00
31	397.36	38.6158	10.95	9.35	0.1045	0.59	0.32	0.0035	0.9478	2989.73	6505.24
32	1605.49	38.0926	10.46	10.41	0.5933	0.80	0.55	0.0100	0.9608	3898.88	6642.57
33	802.89	32.3718	13.30	12.28	0.0615	0.67	0.38	0.0015	0.9658	2900.65	6416.13
34	805.73	32.7229	10.62	10.10	0.0000	0.67	0.38	0.0000	0.9775	3386.69	0.00
35	795.21	33.0729	11.11	10.51	0.0000	0.68	0.40	0.0000	0.9788	3308.33	0.00
36	799.08	32.4496	12.29	11.52	0.0000	0.67	0.39	0.0000	0.9728	3140.04	0.00
37	251.38	32.6025	11.23	9.36	0.0000	0.58	0.28	0.0000	0.9724	3044.00	0.00
38	791.33	43.5084	11.36	10.90	0.4979	0.65	0.42	0.0042	0.9764	3723.71	6835.44
39	801.54	32.3287	13.79	13.01	0.2607	0.65	0.37	0.0034	0.9855	3216.36	6565.29
40	2645.87	32.6288	11.89	9.67	2.5200	0.93	0.74	0.0300	0.9753	5374.21	6847.03
41	800.52	31.8401	9.12	8.55	0.1324	0.68	0.38	0.0008	0.9523	3129.60	6525.04
42	794.69	23.7001	11.82	10.85	0.0000	0.69	0.36	0.0000	0.9704	2849.34	0.00
43	1596.36	39.0830	11.89	11.86	1.4923	0.80	0.50	0.0040	0.9859	4300.32	6869.77
44	1601.56	39.3295	11.39	11.34	1.0621	0.79	0.53	0.0100	0.9434	4129.94	6771.88
45	399.12	27.3123	10.52	8.67	0.0000	0.61	0.28	0.0000	0.9614	2783.97	0.00
46	805.23	31.1355	12.22	11.65	0.0000	0.67	0.39	0.0000	0.9896	3434.78	0.00
47	793.90	43.6298	13.41	12.49	0.3548	0.66	0.41	0.0005	0.9686	3310.01	6614.79
48	803.13	24.6076	11.18	10.47	0.0000	0.70	0.37	0.0000	0.9763	3097.03	0.00

*All numbers in the column for Variable 2 to be multiplied by 10^5.

Table 3 Test Numbers and Coded Levels of Coded Variables

Test No.	Coded Levels of Variables										
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}
25	1.0020	-0.9266	-1.0000	-1.0456	0.0000	1.1717	1.3732	0.0000	-0.7679	0.6023	0.0000
26	-0.9644	-1.0227	0.9764	-0.5937	-1.6443	1.1717	1.4437	-0.7439	1.2273	-1.1729	1.0096
27	0.9981	0.9442	2.0065	1.9752	0.2058	1.0864	1.1536	1.0000	0.7820	0.6485	-2.1435
28	1.0023	-1.0164	-0.4509	0.4429	0.0000	1.2559	1.4437	0.0000	1.5133	0.7718	0.0000
29	-0.9644	0.9986	-0.3735	1.1995	0.0000	-1.3566	-1.1327	0.0000	1.6609	-0.1512	0.0000
30	-0.9879	-0.9881	-0.8127	-2.4328	0.0000	-0.8850	-1.4125	0.0000	-0.5062	-1.6761	0.0000
31	-1.0108	1.0176	-0.6660	-1.9231	0.0000	-1.1168	-0.7473	0.0000	-2.2406	-1.0255	0.0000
32	1.0023	0.9787	-1.0304	-1.0685	0.0793	1.0000	1.3732	1.0000	-0.9192	0.8220	1.2587
33	0.0036	-0.0195	0.8812	0.2462	-2.1701	-0.2328	-0.0745	-2.1514	-0.4157	-1.2357	0.8443
34	0.0090	0.0439	-0.9096	-1.3091	0.0000	-0.2328	0.0745	0.0000	0.7522	-0.1572	0.0000
35	-0.0090	0.1065	-0.5506	-0.0000	0.0000	-0.1298	0.1263	0.0000	0.8811	0.6102	0.0000
36	-0.0018	-0.0054	0.2527	0.2622	-0.0000	0.2328	0.0272	0.0000	0.2847	0.5030	0.0000
37	-1.6723	0.0223	-0.3529	-1.9146	0.0000	-1.2357	-1.2701	0.0000	0.2448	-0.8988	0.0000
38	-0.0163	1.7191	-0.3735	-0.7025	-0.0947	-0.4435	0.3174	-0.4411	0.6430	0.5024	1.6016
39	0.0018	-0.0273	1.1691	0.7058	-0.7369	-0.4435	-0.1789	-0.7921	1.5428	-0.5159	1.1191
40	1.7252	0.0270	-0.0106	-0.7025	1.5149	2.0468	2.5349	2.8250	0.5337	4.1062	1.6227
41	0.0000	-0.1169	-2.1213	-2.6350	-1.4094	-0.1298	-0.0745	-3.1957	-1.7811	0.4962	1.0459
42	-0.0108	-1.8530	-0.0576	-0.7390	0.0000	-0.0283	-0.2862	0.0000	0.0451	0.3036	0.0000
43	0.9964	1.0883	-0.0106	-0.0307	0.9949	1.0000	1.0000	-0.5221	1.5822	1.5031	1.6610
44	1.0009	1.1253	-0.3525	-0.3875	0.6573	0.9126	0.8550	1.0000	-2.6919	1.2207	1.4906
45	-1.0036	-1.0188	-0.9849	-2.5241	0.0000	-0.8850	-1.2701	0.0000	-0.8586	0.2559	0.0000
46	0.0090	-0.2485	0.2072	-0.1729	0.0000	-0.2328	0.0272	0.0000	1.8475	0.6872	0.0000
47	-0.0127	1.7355	0.9468	0.3817	-0.4310	-0.3374	0.2230	-3.9764	-0.1349	0.6113	1.2096
48	0.0054	-1.6321	-0.5006	-1.0228	0.0000	0.0717	-0.1789	0.0000	0.6331	0.4747	0.0000

Table 4. Analysis of Variance of 10 Tests
First Order Model of 3 Variables
Life predicting equation:

$$\hat{y} = 3.52 + 0.0538x_1 - 0.341x_2 - 0.0514x_3$$

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio
Due to Mean	0.0100	1	0.0100	
Due to Variance	0.8439	1	0.8439	
Due to Zero Upcrossings	0.0264	1	0.0264	
Due to Regression	0.8857	3	0.2952	
Residuals	0.4094	6	0.0682	4.328
Total	1.2951	9		

F-ratio is smaller than the table value of 4.76 with 3 and 6 degrees of freedom at 95% significance level. So regression is not effective and the model is rejected.

Table 5. **Results of 10 Tests, First Order Model of 3 Significant Variables**
Life predicting equation:

$$\hat{y} = 3.52 + 0.0538x_1 - 0.341x_2 - 0.0516x_3$$

Test No.	Actual Life		Predicted Life		Residuals	95% Confidence Interval			
						$\hat{y}$		$\hat{T}$	
	T	y	$\hat{y}$	$\hat{T}$	$y-\hat{y}$	Lower	Upper	Lower	Upper
25	49.58	3.904	3.940	51.42	-0.036	3.502	4.378	33.18	79.68
26	50.75	3.927	3.766	43.21	0.161	3.323	4.208	27.75	67.28
27	18.41	2.913	3.147	23.27	-0.234	2.628	3.666	13.85	39.09
28	52.50	3.957	3.896	49.21	0.061	3.500	4.302	32.79	73.86
29	22.33	3.106	3.249	25.76	-0.143	2.909	3.589	18.34	36.20
30	30.67	3.423	3.844	46.72	-0.421	3.440	4.248	31.19	83.77
31	24.00	3.178	3.151	23.36	0.027	2.674	3.628	14.49	37.64
32	30.00	3.401	3.291	26.87	0.110	2.899	3.683	18.16	39.75
33	40.92	3.712	3.480	32.46	0.232	3.198	3.761	24.50	43.01
34	44.42	3.794	3.551	34.85	0.243	3.282	3.820	26.62	45.62

Table 6. Analysis of Variance of 18 Tests
First Order Model of 3 Variables
Life predicting equation:

$$\hat{y} = 3.55 + 0.0242x_1 - 0.327x_2 - 0.0597x_3$$

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Ratio
Due to Mean	0.0108	1	0.0108	
Due to Variance	1.4728	1	1.4728	
Due to Zero Upcrossings	0.0572	1	0.0572	
Due to Regression	1.5407	3	0.5136	
Residuals	0.4862	14	0.0347	14.80
Total	2.0269	17		

F-ratio is greater than the F value of 3.34 from the table with 3 and 14 degrees of freedom at 95% significance level. So regression is effective and the model is accepted.

Table 7. Results of 18 Tests, First Order Model of 3 Variables
Life predicting equation:

$$\hat{y} = 3.55 + 0.0242x_1 - 0.327x_2 - 0.0597x_3$$

Test	Actual Life		Predicted Life		Residuals	95% Confidence Interval			
						$\hat{y}$		$\hat{T}$	
No.	T	y	$\hat{y}$	$\hat{T}$	$y-\hat{y}$	Lower	Upper	Lower	Upper
25	49.58	3.904	3.934	51.11	-0.030	3.732	4.136	41.79	62.53
26	50.75	3.927	3.800	44.70	0.127	3.581	4.109	35.93	55.62
27	18.41	2.913	3.142	23.15	-0.229	2.873	3.411	17.69	30.29
28	52.50	3.957	3.876	48.23	0.081	3.699	4.053	40.41	57.57
29	22.33	3.106	3.265	26.18	-0.159	3.088	3.432	21.93	30.92
30	30.67	3.423	3.894	49.11	-0.471	3.704	4.084	40.61	59.39
31	24.00	3.178	3.229	25.25	-0.051	3.021	3.437	20.52	31.08
32	30.00	3.401	3.312	27.44	0.089	3.120	3.504	22.64	33.26
33	40.92	3.712	3.500	33.16	0.212	3.358	3.642	28.73	38.17
34	44.42	3.794	3.587	36.13	0.207	3.462	3.712	31.89	40.92
35	38.17	3.642	3.545	34.64	0.097	3.440	3.650	31.19	38.47
36	36.92	3.609	3.533	34.23	0.076	3.428	3.638	30.82	38.01
37	33.08	3.498	3.520	33.78	-0.022	3.297	3.743	27.04	42.22
38	23.33	3.150	3.006	20.21	0.144	2.792	3.220	16.31	25.03
39	30.83	3.429	3.486	32.66	-0.057	3.320	3.652	27.66	38.55
40	32.17	3.471	3.580	35.87	-0.109	3.375	3.786	29.21	44.05
41	40.42	3.693	3.711	40.89	-0.018	3.488	3.934	32.72	51.10
42	71.33	4.267	4.156	63.82	0.111	3.935	4.377	51.18	79.57

Table 8. Analysis of Variance of 18 Tests
First Order Model of 11 Variables

Life predicting equation:

$$\hat{y} = 3.39 - 0.0143x_1 - 0.463x_2 - 0.144x_3 - 0.0200x_4 - 0.314x_5 - 0.727x_6 + 0.637x_7 + 0.112x_8 + 0.0103x_9 + 0.101x_{10} - 0.0803x_{11}$$

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio
Due to Mean	0.0108	1	0.0108	
Due to Variance	1.4728	1	1.4728	
Due to Zero Upcrossings	0.0572	1	0.0572	
Due to Level Upcrossings				
of ε_f Level	0.0009	1	0.0009	
of ε_y Level	0.0794	1	0.0794	
Due to Duration of Excursion Above Zero Level	0.0349	1	0.0349	
Due to Duration of Excursion Above ε_f Level	0.1650	1	0.1650	
Above ε_y Level	0.0015	1	0.0015	
Due to Band Width	0.0002	1	0.0002	
Due to Average Amplitude				
Above ε_f Level	0.0097	1	0.0097	
Above ε_y Level	0.0262	1	0.0262	
Due to Regression	1.8587	11	0.1690	
Residuals	0.1682	6	0.0280	6.036
Total	2.0269	17		

F-ratio is greater than the table value of 2.92 with 11 and 6 degrees of freedom at 95% significance level. So regression is effective, and the model is accepted.

Table 9. Results of 18 Tests, First Order Model of all 11 Variables
Life predicting equation:

$$\hat{y} = 3.39 - 0.0143x_1 - 0.463x_2 - 0.144x_3 + 0.200x_4 - 0.314x_5 - 0.727x_6 + 0.637x_7 + 0.112x_8 + 0.0103x_9 - 0.101x_{10} - 0.083x_{11}$$

Test No.	Actual Life		Predicted Life		Residuals	95% Confidence Interval			
						$\hat{y}$		$\hat{T}$	
	T	y	$\hat{y}$	$\hat{T}$	$y-\hat{y}$	Lower	Upper	Lower	Upper
25	49.58	3.904	4.00o	54.65	-0.097	3.676	4.326	39.47	75.67
26	50.75	3.927	4.037	56.66	-0.110	3.665	4.409	39.06	82.18
27	18.41	2.913	2.925	18.63	-0.012	2.524	3.326	12.47	27.84
28	52.50	3.957	3.887	48.76	0.070	3.591	4.183	36.27	65.57
29	22.33	3.106	3.254	25.89	-0.148	2.902	3.606	18.20	36.83
30	30.67	3.423	3.497	33.02	-0.074	3.115	3.789	22.54	48.36
31	24.00	3.178	3.234	25.38	-0.056	2.865	3.603	17.54	36.73
32	30.00	3.401	3.254	25.89	0.147	2.919	3.589	18.52	36.21
33	40.92	3.712	3.640	38.09	0.072	3.297	3.983	27.04	53.66
34	44.42	3.794	3.617	37.23	0.177	3.355	3.789	28.65	48.37
35	38.17	3.642	3.662	38.94	-0.020	3.439	3.885	31.16	48.65
36	36.92	3.609	3.588	36.16	0.021	3.390	3.786	29.66	44.09
37	33.08	3.498	3.490	32.79	0.008	3.089	3.891	21.95	48.97
38	23.33	8.150	3.064	21.41	0.086	2.741	3.387	15.50	29.58
39	30.83	3.429	3.465	31.98	-0.036	3.169	3.761	23.78	42.99
40	32.17	3.471	3.579	35.84	-0.108	3.200	3.958	24.53	52.37
41	40.42	3.693	3.772	43.47	-0.079	3.383	4.161	29.46	64.14
42	71.33	4.267	4.109	60.89	0.158	3.822	4.395	45.73	81.07

Table 10. Analysis of Variance of 24 Tests
First Order Model of 3 Variables
Life predicting equation:

$$\hat{y} = 3.56 + 0.0195x_1 - 0.325x_2 - 0.0518x_3$$

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio
Due to Mean	0.1223	1	0.1223	
Due to Variance	2.3905	1	2.3905	
Due to Zero Upcrossings	0.0482	1	0.0482	
Due to Regression	2.5609	3	0.8536	
Residuals	0.6192	20	0.0310	27.54
Total	3.1801	23		

F-ratio is greater than the table value of 3.10 with 3 and 20 degrees of freedom at 95% significance level. So regression is effective, and the model is accepted.

Table 11. Results of 24 Tests, First Order Model of 3 Variables
Life predicting equation:

$$\hat{y} = 3.56 + 0.0195x_1 - 0.0325x_2 - 0.0518x_3$$

Test No.	Actual Life		Predicted Life		Residuals	95 % Confidence Interval			
						$\hat{y}$		$\hat{T}$	
	T	y	$\hat{y}$	$\hat{T}$	$y-\hat{y}$	Lower	Upper	Lower	Upper
25	49.58	3.904	3.932	51.01	-0.028	3.767	4.097	43.26	60.15
26	50.75	3.927	3.823	45.74	0.104	3.644	4.002	38.23	54.73
27	18.41	2.913	3.167	23.74	-0.254	2.958	3.376	19.27	29.24
28	52.50	3.957	3.886	48.72	0.071	3.727	4.045	41.57	57.08
29	22.33	3.106	3.272	26.36	-0.166	3.147	3.397	23.26	29.88
30	30.67	3.423	3.904	49.60	-0.481	3.760	4.048	42.95	57.28
31	24.00	3.178	3.243	25.61	-0.065	3.072	3.414	21.58	30.39
32	30.00	3.401	3.314	27.49	0.087	3.162	3.466	23.61	32.02
33	40.92	3.712	3.520	33.78	0.192	3.403	3.637	30.06	37.97
34	44.42	3.794	3.592	36.31	0.202	3.492	3.692	32.85	40.13
35	38.17	3.642	3.553	34.92	0.089	3.469	3.636	32.12	37.96
36	36.92	3.609	3.548	34.74	0.061	3.465	3.631	31.96	37.77
37	33.08	3.498	3.538	34.40	-0.040	3.352	3.724	28.57	41.42
38	23.33	3.150	3.019	20.41	0.131	2.860	3.177	17.47	23.99
39	30.83	3.429	3.508	33.38	-0.079	3.370	3.646	29.09	38.31
40	32.17	3.471	3.585	36.05	-0.114	3.416	3.754	30.45	42.69
41	40.42	3.693	3.707	40.73	-0.014	3.521	3.893	33.83	49.04
42	71.33	4.267	4.165	64.39	0.102	4.000	4.330	54.61	75.93
43	19.75	2.983	3.225	25.15	-0.242	3.100	3.350	22.19	28.51
44	29.92	3.398	3.231	25.30	0.167	3.100	3.344	22.19	28.34
45	48.17	3.875	3.922	50.50	-0.047	3.772	4.072	43.46	58.68
46	44.50	3.795	3.630	37.71	0.165	3.544	3.716	34.62	41.08
47	21.00	3.046	2.945	19.01	0.101	2.770	3.120	15.96	22.65
48	64.92	4.173	4.116	61.31	0.057	3.966	4.266	52.76	71.25

Table 12. Analysis of Variance of 24 Tests
First Order Model of 11 Variables
Life predicting equation:

$$\hat{y} = 3.50 - 0.0105x_1 - 0.398x_2 - 0.0748x_3 + 0.0459x_4 - 0.111x_5 - 0.317x_6 + 0.290x_7 + 0.0091x_8 - 0.0383x_9 + 0.0739x_{10} + 0.0231x_{11}$$

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio
Due to Mean	0.1223	1	0.1223	
Due to Variance	2.3905	1	2.3905	
Due to Zero Upcrossings	0.0482	1	0.0482	
Due to Level Upcrossings				
of ε_f Level	0.0006	1	0.0006	
of ε_y Level	0.0838	1	0.0838	
Due to Duration of Excursion Above Zero Level	0.0180	1	0.0180	
Due to Duration of Excursion Above ε_f Level	0.1010	1	0.1010	
Above ε_y Level	0.0006	1	0.0006	
Due to Band Width	0.0238	1	0.0238	
Due to Average Amplitude				
Above ε_f Level	0.0362	1	0.0362	
Above ε_y Level	0.0054	1	0.0054	
Due to Regression	2.8302	11	0.2573	
Residuals	0.3498	12	0.0292	8.812
Total	3.1801	23		

F-ratio is greater than the table value of 2.73 with 11 and 12 degrees of freedom at 95% significance level. So regression is effective, and the model is accepted.

Table 13. **Results of 24 Tests, First Order Model of all 11 Variables Life predicting equation:**

$$\hat{y} = 3.50 - 0.0105x_1 - 0.398x_2 - 0.0748x_3 + 0.0459x_4 - 0.111x_5 - 0.317x_6 + 0.297x_7 + 0.0091x_8 - 0.0383x_9 + 0.0734x_{10} + 0.0231x_{11}$$

Test No.	Actual Life		Predicted Life		Residuals	95% Confidence Interval			
						$\hat{y}$		$\hat{T}$	
	T	y	$\hat{y}$	$\hat{T}$	$y-\hat{y}$	Lower	Upper	Lower	Upper
25	49.58	3.904	3.990	54.05	-0.086	3.717	4.262	41.17	70.98
26	50.75	3.927	3.934	51.11	-0.007	3.620	4.248	37.35	69.95
27	18.41	2.913	3.004	20.17	-0.091	2.651	3.357	14.17	28.70
28	52.50	3.957	3.904	49.60	0.053	3.693	4.115	40.15	61.25
29	22.33	3.106	3.207	24.70	-0.101	2.908	3.506	18.33	33.30
30	30.67	3.423	3.624	37.49	-0.201	3.347	3.901	28.42	49.44
31	24.00	3.178	3.235	25.41	-0.057	2.939	3.531	18.89	34.17
32	30.00	3.401	3.339	28.19	0.062	3.119	3.559	22.62	35.13
33	40.92	3.712	3.675	39.45	0.037	3.396	3.954	29.85	52.14
34	44.42	3.794	3.530	34.12	0.264	3.362	3.698	28.85	40.36
35	38.17	3.642	3.592	36.31	0.050	3.439	3.745	31.17	42.29
36	36.92	3.609	3.584	36.02	0.025	3.451	3.717	31.53	41.14
37	33.08	3.498	3.575	35.69	-0.077	3.200	3.930	25.02	50.92
38	23.33	3.150	3.105	22.31	0.045	2.878	3.332	17.78	27.98
39	30.83	3.429	3.548	34.74	-0.119	3.324	3.772	27.76	43.48
40	32.17	3.471	3.702	40.53	-0.231	3.390	4.010	29.68	55.35
41	40.42	3.693	3.864	47.66	-0.171	3.550	4.178	34.82	65.22
42	71.33	4.267	4.160	64.07	0.107	3.946	4.374	51.75	79.32
43	19.75	2.983	3.007	20.23	-0.024	2.793	3.312	16.34	27.44
44	29.92	3.398	3.178	23.99	0.220	2.886	3.470	17.92	32.14
45	48.17	3.875	3.843	46.67	0.032	3.551	4.096	34.85	60.10
46	44.50	3.795	3.642	38.17	0.153	3.476	3.808	32.34	45.04
47	21.00	3.046	3.022	20.53	0.024	2.697	3.347	14.84	28.41
48	64.92	4.173	4.081	59.20	0.092	3.915	4.247	50.17	69.87

Table 14. Comparison of Percent Deviations of Predicted Lives and Residual Sum of Squares for Five Models

Test No.	Actual Life T	Percent Deviations of Predicted Lives				
		Eq(1)	Eq(2)	Eq(3)	Eq(4)	Eq(5)
25	49.58	-3.7	-3.1	-10.2	-2.9	-9.0
26	50.75	14.9	11.9	-11.6	9.9	-0.7
27	18.41	-26.4	-25.7	-2.0	-28.9	-9.6
28	52.50	6.3	8.1	7.1	7.2	5.5
29	22.33	-15.4	-17.2	-15.9	-18.0	-10.6
30	30.67	-52.3	-60.1	-7.7	-61.7	-22.2
31	24.00	2.7	-5.2	-5.7	-6.7	-5.8
32	30.00	10.4	8.5	13.7	8.4	6.0
33	40.92	2.1	19.0	6.9	17.4	3.6
34	44.42	21.5	18.5	16.2	-22.3	23.2
35	38.17		9.2	-2.0	8.5	5.3
36	36.92		7.3	2.1	5.9	2.4
37	33.08		-2.1	0.9	-4.0	-7.9
38	23.33		13.3	8.2	12.5	4.4
39	30.83		-5.9	-3.7	-8.3	-12.7
40	32.17		-11.5	-11.4	-12.1	-26.0
41	40.42		-1.1	-7.5	-0.8	-17.9
42	71.33		10.5	14.6	9.7	10.2
43	19.75				-27.3	-2.4
44	29.92				15.4	19.8
45	48.17				-4.8	3.1
46	44.50				15.3	14.2
47	21.00				9.5	2.2
48	64.92				5.6	8.8
		Average Deviations				
Negative side		24.5	14.7	7.8	16.5	13.4
Positive side		9.7	11.8	8.7	10.4	8.4
		Residuals				
Percent residual sum of squares of the total		32.6	24.0	8.3	20.5	11.0

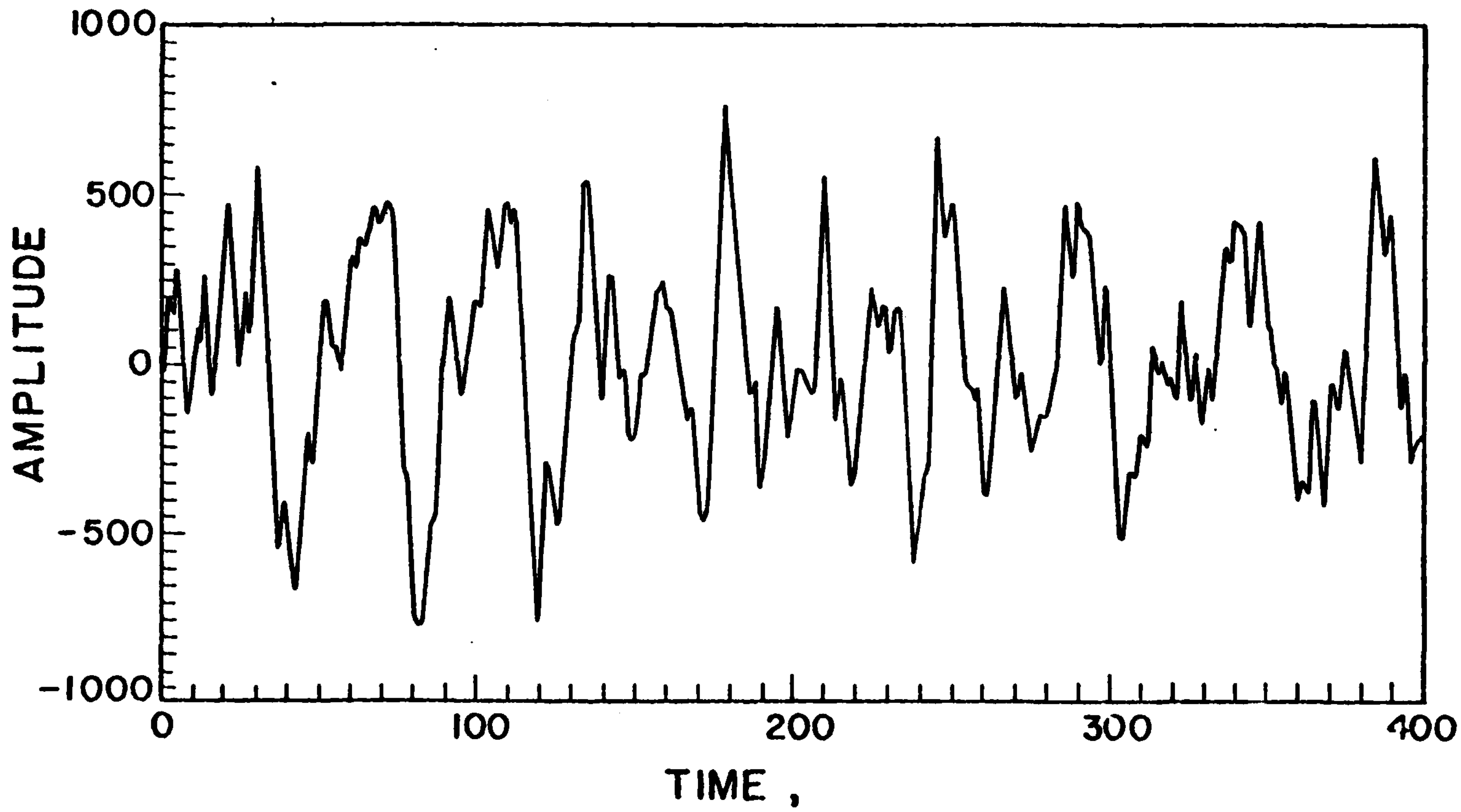

Fig. 1 Typical Response Signal of a Test Specimen

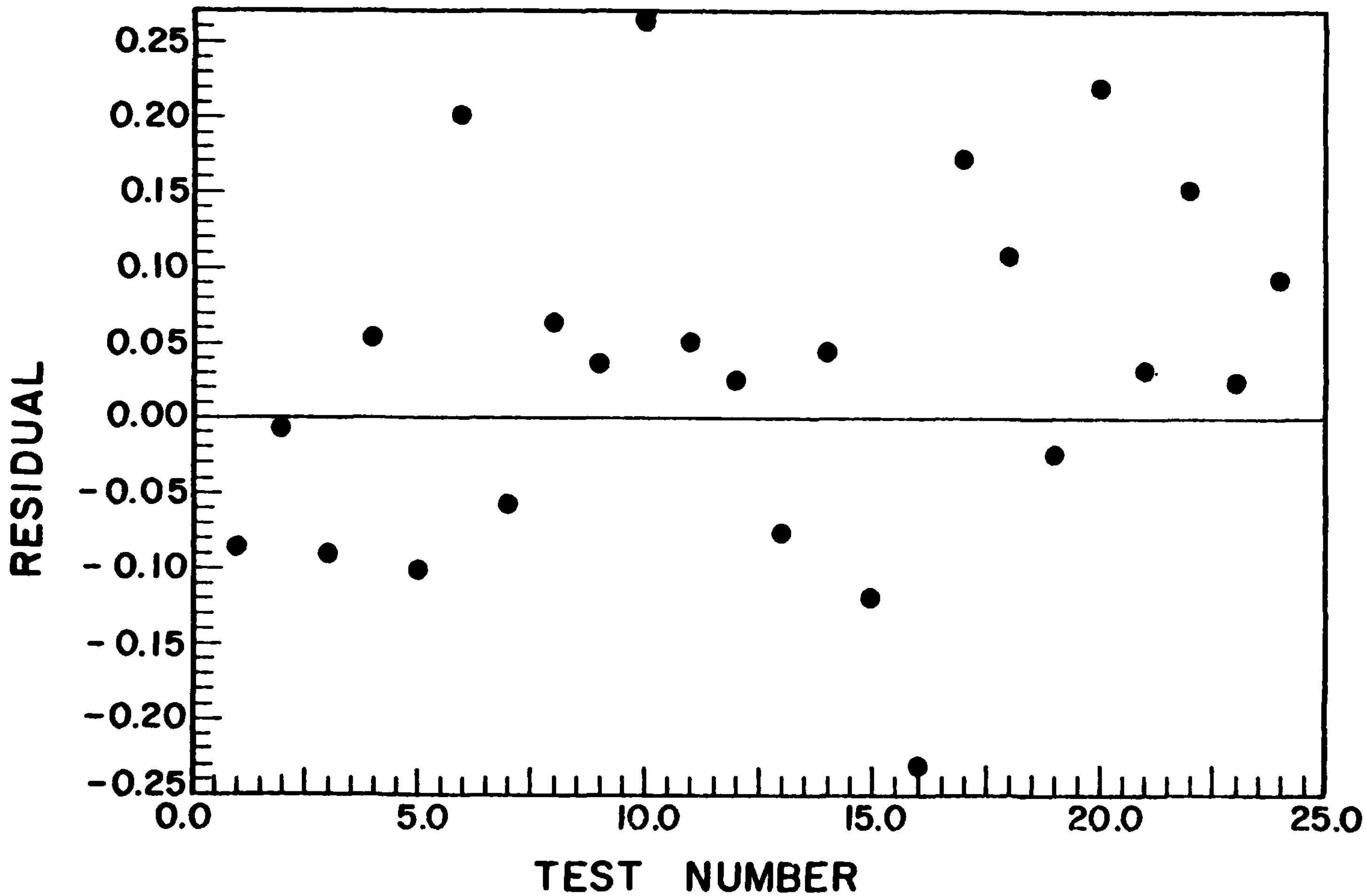

Fig. 2 Distribution of Residuals for the Best First Order Model, Eq. (5)

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: UW/RF-5	2. GOVT ACCESSION NO.: AD-A090694	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Experimental Random Fatigue in Elastic-Plastic Range - First Order Models.		5. TYPE OF REPORT & PERIOD COVERED: 1978-1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): T. C. Huang [redacted] Vinod K. Nagpal		8. CONTRACT OR GRANT NUMBER(s): N00014-76-C-0825
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of Engineering Mechanics, University of Wisconsin, Madison, Wisconsin 53706		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: NR064-576
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Department of the Navy, Arlington, Virginia 22217		12. REPORT DATE: Aug[redacted]79
		13. NUMBER OF PAGES: 31
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Office of Naval Research, Chicago Branch Office, 536 S. Clark St., Chicago, Illinois 60605		15. SECURITY CLASS. (of this report): Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Random fatigue
Random fatigue in elastic-plastic range
Fatigue under multi-probablistic-factors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experiment program, based on 11 probabilistic parameters and 3 experiment designs was conducted for 24 specimens for fatigue of materials in an elastic-plastic range under random vibrations. The magnitude levels of all probabilistic parameters are completed from the spectral moments and coded. By regressing the log of fatigue life on the corresponding coded parameters, the first-order regression models are developed.

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

Unclassified
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410727