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A NEW TEST OF NORMALITY AND OF EXPONENTIALITY  
CALLED THE Q-TEST

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## FOREWORD

The research work reported herein was conducted by Prof. Dr. Waloddi Weibull, Chemin Fontanettaz 15, 1012 Lausanne, Switzerland under USAF Contract No. F44620-73-C-0066. This contract, which was initiated under Project No. 7351, "Metallic Materials", Task 735106, "Behavior of Metals", was administered by the European Office of Aerospace Research. The work was monitored by the Metals and Ceramics Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under the direction of Mr. W. J. Trapp, AFML/LL.

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## 1. INTRODUCTION

The log-normal function has frequently been proposed as the appropriate statistical model of fatigue life distributions. Also, the exponential distribution function has been advocated for this purpose, in particular by Epstein et al. (1,2).

In view of the necessity of using the correct distribution function when analyzing a given sample of test data, it is important to find sharp tests for deciding whether the assumed function is the correct one or not.

A new test which seems to be quite sensitive to outliers within the sample will now be presented.

## 2. THE TEST STATISTIC Q

Let  $x_1, \dots, x_N$  be the ordered elements of a sample drawn from a normal population with unknown parameters  $m$  and  $\sigma$ . From these elements an unbiased and asymptotically efficient estimate of  $\sigma$  is given by

$$\hat{\sigma}_1 = \sqrt{\sum (x_i - \bar{x})^2 / (N-1)} = \sqrt{(\sum x_i^2 - N\bar{x}^2) / (N-1)} \quad (1)$$

It is, however, possible to obtain another, also unbiased, estimate  $c_2$  by using the best, linear, unbiased estimator, which consists in multiplying each observation by an appropriate coefficient  $a_i$ , thus arriving at

$$\hat{\sigma}_2 = \sum a_i \cdot x_i \quad (2)$$

The coefficients  $a_i$  have been computed and tabulated for complete and censored samples, for instance, by Sarhan & Greenberg (3). Values for complete samples of the sizes  $N = 5(1)20$  are listed in Table 1.

Even if these two estimates are unbiased, it is evident that their values will never be exactly equal for any given sample, because they will react differently for the same deviations of the elements. For instance, for any variation  $\Delta x_i$  of the  $i$ :th element the variation of  $\hat{\sigma}_1$  is independent of the order number  $i$ , whereas the variation of  $\hat{\sigma}_2$ , as being equal to  $a_i \Delta x_i$ , is much larger for the order numbers  $i=1$  and  $i=N$  than for other order numbers and even equal to zero for  $i = (N+1)/2$ , as is easily read from Table 1.

It thus seemed plausible that the quotient

$$Q = \hat{c}_1 / \hat{c}_2 \quad (3)$$

used as a test statistic, may provide a test which is sensitive to deviations in the extreme elements of the sample. This is a valuable property, in particular when testing samples of fatigue performance data, which are frequently composed of two or even three parts belonging to different populations.

Introducing (1) and (2) into (3) we arrive at the test statistic

$$Q = \sqrt{(\sum x_i^2 - N \bar{x}^2) / (N-1)} / \sum a_i \cdot x_i \quad (4)$$

where  $\bar{x} = \sum x_i / N$  and the coefficients  $a_i$  are given in Table 1.

The properties and the use of the statistic  $Q$  have been examined as indicated in the following.

### 3. PROPERTIES OF THE STATISTIC $Q$

It is easily proved that, due to the condition  $\sum a_i = 0$ , the sampling distribution of  $Q$  is both a scale and location invariant and depending only on the shape of the distribution function. Thus it can be used as a shape estimator and also for testing the hypothesis that the sample is drawn from the assumed population.

All relevant properties of  $Q$  are given by its sampling distribution. To this purpose these distributions have been computed by use of Program 8/73 for normal distributions and for Weibull distributions with the parameters  $\alpha = 1/m = 0.1, 0.4, 0.7, 1.0$  and for sample sizes  $N = 5, 10, 15, 20$ . The number of generated random samples in this Monte-Carlo study were 10,000 for  $N=5$  and 10 and 5,000 for  $N=15$  and 20.

This program does also provide the percentiles of  $Q$  corresponding to the percentages 1%, 2%, 5%, 50%, 95%, 98%, and 99%. Computed values are given in Table 2.

By use of these sampling distributions also the decision power  $DP$  of  $Q$  has been computed for sample sizes  $N=10$  and 20. The results are presented in Table 3.

### 4. THE $Q$ -TEST OF NORMALITY

The percentiles  $q_p$  from the normal distribution given in Table 2 can now be used as the limits of the rejection regions of the test statistic  $Q$  defined by (4). These limits are interpolated for all sample sizes between 5 and 20, as indicated in Figure 1.

## 5. THE Q-TEST OF EXPONENTIALITY

In the same way, the hypothesis that the sample is drawn from an exponential population ( $m=1$ ) can be tested. The limits are given in Figure 2.

6. REFERENCES

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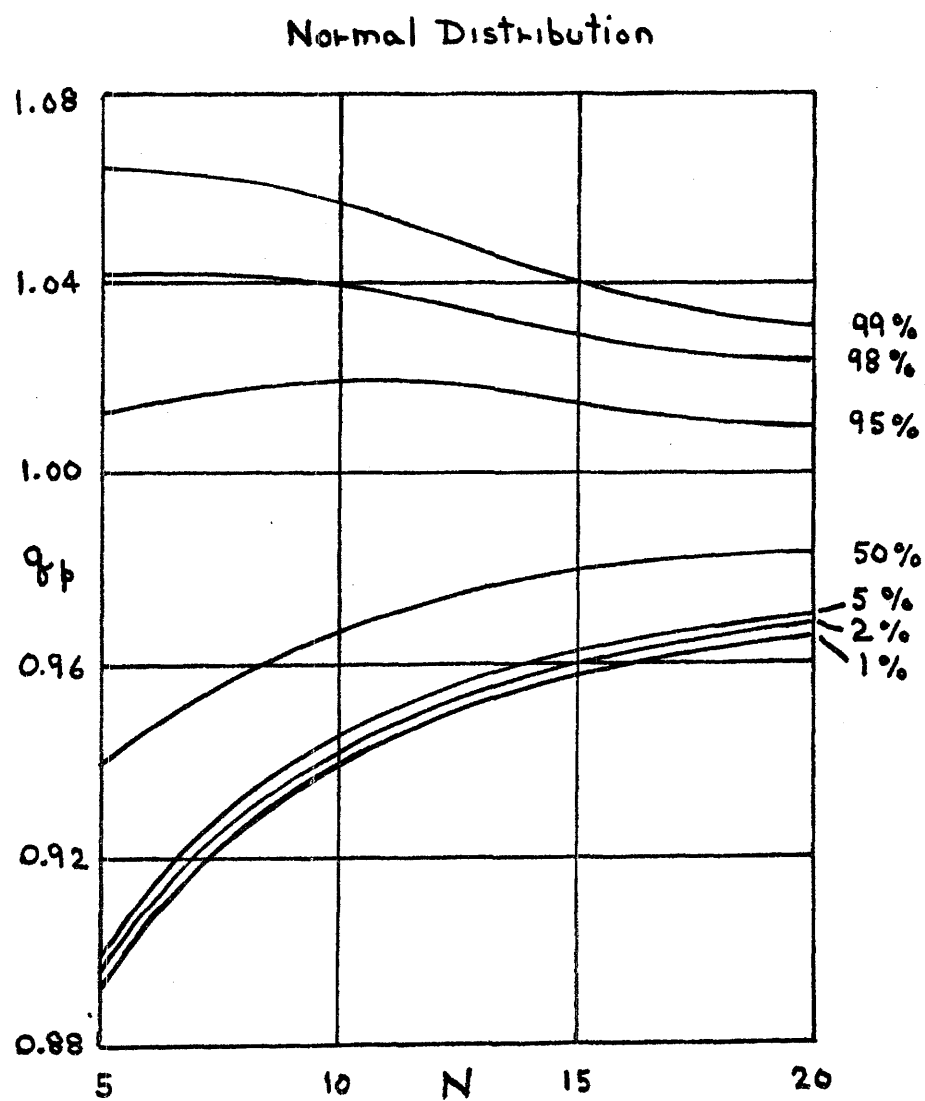


Figure 1. Percentiles of Q as Functions of the Sample Size N.

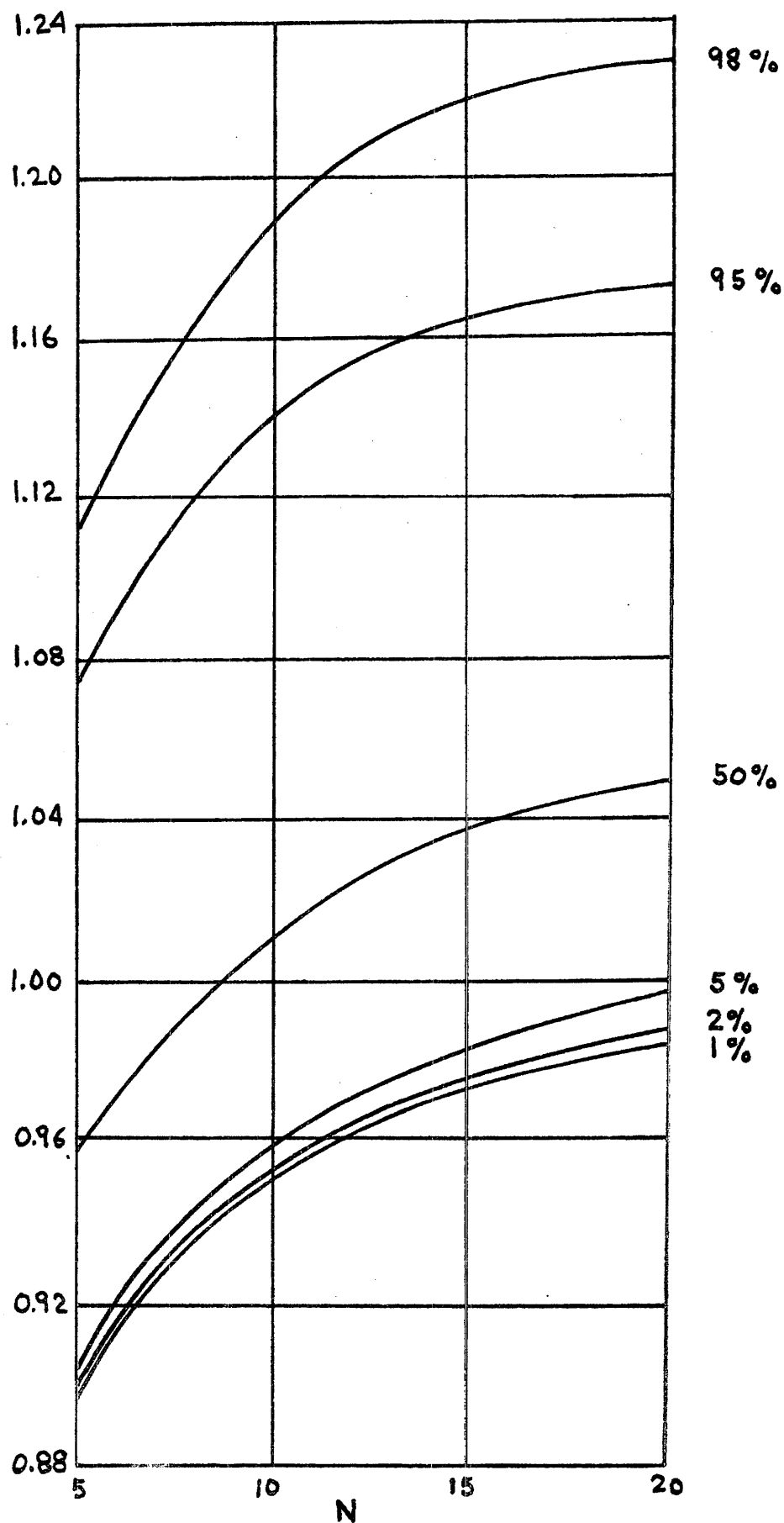


Figure 2. Percentiles of  $Q$  as Functions of  $N$ ; Exponential dbn.

TABLE 1. VALUES OF THE COEFFICIENTS  $a_i$ 

$i \backslash N$	5	6	7	8	9	10	11	12
1	-.3724	-.3175	-.2778	-.2476	-.2237	-.2044	-.1883	-.1748
2	-.1352	-.1386	-.1351	-.1294	-.1233	-.1172	-.1115	-.1061
3	.0000	-.0432	-.0625	-.0713	-.0751	-.0763	-.0760	-.0749
4	.1352	.0432	.0000	-.0230	-.0360	-.0436	-.0481	-.0506
5	.3724	.1386	.0625	.0230	.0000	-.0142	-.0234	-.0294
6	-	.3175	.1351	.0713	.0360	.0142	.0000	-.0097
7	-	-	.2778	.1294	.0751	.0436	.0234	.0097
8	-	-	-	.2476	.1233	.0763	.0481	.0294
9	-	-	-	-	.2237	.1172	.0760	.0506
10	-	-	-	-	-	.2044	.1115	.0749
11	-	-	-	-	-	-	.1883	.1061
12	-	-	-	-	-	-	-	.1748

$i \backslash N$	13	14	15	16	17	18	19	20
1	-.1632	-.1532	-.1444	-.1366	-.1297	-.1235	-.1178	-.1128
2	-.1013	-.0968	-.0927	-.0889	-.0854	-.0822	-.0792	-.0765
3	-.0735	-.0717	-.0699	-.0681	-.0663	-.0645	-.0628	-.0611
4	-.0520	-.0526	-.0526	-.0524	-.0519	-.0512	-.0505	-.0497
5	-.0335	-.0362	-.0379	-.0391	-.0398	-.0401	-.0402	-.0402
6	-.0164	-.0212	-.0247	-.0272	-.0290	-.0302	-.0312	-.0318
7	.0000	.0070	.0122	.0160	.0189	.0211	.0228	.0241
8	.0164	.0070	.0000	-.0053	-.0094	-.0125	-.0150	-.0169
9	.0335	.0212	.0122	.0053	.0000	-.0041	-.0074	-.0101
10	.0520	.0362	.0247	.0160	.0094	.0041	.0000	-.0033
11	.0735	.0526	.0379	.0272	.0189	.0125	.0074	.0033
12	.1013	.0717	.0526	.0391	.0290	.0211	.0150	.0101
13	.1632	.0968	.0699	.0524	.0398	.0302	.0228	.0169
14	-	.1532	.0927	.0681	.0519	.0401	.0312	.0241
15	-	-	.1444	.0889	.0663	.0512	.0402	.0318
16	-	-	-	.1366	.0854	.0645	.0505	.0402
17	-	-	-	-	.1297	.0822	.0628	.0497
18	-	-	-	-	-	.1235	.0792	.0611
19	-	-	-	-	-	-	.1178	.0765
20	-	-	-	-	-	-	-	.1128

TABLE 2. PERCENTILES OF Q FOR VARIOUS SAMPLE SIZES.

Sample size	Percentage	Normal dbn.	Weibull distribution			
			0.1	0.4	0.7	1.0
5	1	0.894	0.895	0.894	0.895	0.896
5	2	0.896	0.896	0.896	0.897	0.898
5	5	0.899	0.900	0.900	0.901	0.904
5	50	0.933	0.934	0.934	0.942	0.955
5	95	1.013	1.018	1.014	1.036	1.074
5	98	1.042	1.052	1.046	1.071	1.112
5	99	1.064	1.078	1.068	1.097	1.130
10	1	0.941	0.942	0.941	0.944	0.949
10	2	0.943	0.944	0.943	0.947	0.953
10	5	0.946	0.947	0.947	0.952	0.960
10	50	0.968	0.972	0.969	0.985	1.011
10	95	1.019	1.033	1.021	1.071	1.142
10	98	1.041	1.059	1.040	1.105	1.194
10	99	1.059	1.085	1.054	1.132	1.231
15	1	0.959	0.960	0.959	0.964	0.972
15	2	0.960	0.961	0.961	0.966	0.976
15	5	0.962	0.964	0.963	0.970	0.983
15	50	0.979	0.983	0.980	1.000	1.035
15	95	1.014	1.036	1.020	1.077	1.164
15	98	1.027	1.062	1.036	1.114	1.221
15	99	1.040	1.079	1.053	1.141	1.260
20	1	0.967	0.968	0.968	0.974	0.985
20	2	0.968	0.970	0.970	0.976	0.989
20	5	0.971	0.972	0.972	0.980	0.997
20	50	0.984	0.989	0.986	1.010	1.049
20	95	1.010	1.035	1.017	1.080	1.173
20	98	1.024	1.055	1.031	1.112	1.228
20	99	1.030	1.071	1.045	1.142	1.278

TABLE 3. DECISION POWER DP OF Q

N = 10

$\alpha$ \ $\alpha$	0.1	0.4	0.7	1.0	normal
0.1	-	5.4	19.8	44.3	7.8
0.4	5.4	-	24.9	49.4	3.1
0.7	19.8	24.9	-	26.4	26.9
1.0	44.3	49.4	26.4	-	50.8
normal	7.9	3.1	26.9	50.8	-

N = 20

$\alpha$ \ $\alpha$	0.1	0.4	0.7	1.0	normal
0.1	-	11.2	37.6	69.1	16.8
0.4	11.2	-	48.2	77.5	7.1
0.7	37.6	48.2	-	40.8	53.9
1.0	69.1	77.5	40.8	-	81.1
normal	16.8	7.1	53.9	81.1	-