A STUDY OF THE METHOD FOR CALCULATING FATIGUE DAMAGE OF AIRCRAFT BY USING RECORDED LOAD FACTORS

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Abstract

A study of the method for calculating fatigue damage of aircraft by using recorded load factors is presented in this paper. Through a systematical calculation by using 35000 hours of flight data recorded from two types of aircraft, each consisting 30 aircraft, it has been prove that this method is a powerful tool to monitor aircraft fatigue damage consumptions.

1 Introduction

It is well known that the best way to manage aircraft structural life is to monitor fatigue damage consumption of each aircraft in the fleet. Due to the shortage of effective and reliable equipment of recording flight parameters, the method of managing by monitoring fatigue damage of individual aircraft can not be applied on old types of aircraft. However, with more and more new types of aircraft getting into service, this situation has been changed, for each aircraft of new types has equipped with flight parameter recorder (FPR) system. The parameters recorded can meet the needs of aircraft fatigue damage monitoring.

The actual service load history of each aircraft obtained by FPR has laid the foundation for the aircraft structural life management. However, the other key task must be done before putting the aircraft fatigue monitoring program into operation. That is to choice a suitable method for calculating fatigue damage based on the recorded flight parameters.

There are many different methods available in the actual practices for calculating fatigue damage at critical locutions in the airframe with different terms of quantifiable metrics to represent the calculated results. For example, US Navy's F/A-18 and P-3 fleets use local strain method with FLE (fatigue life expended). US AF's F-15, F-16 and F-22 fleets use crack growth method with EFH (equivalent flight hours)[1-3]. RAF's Hawk and Tornado fleets use stress method with FI (fatigue index).[4-5]. And combat fleets in RAAF and CF use FLEI (fatigue life expended index) [2, 6-7] to describe the fatigue damage consumption.

After fatigue damage including damage rate per hour (per flight and per mission) under the actual individual aircraft load history as well as the design spectrum being calculated, no matter which term of metric mentioned above is used, operators can manage the structural life of the fleet accordingly by taking flowing measures:

- To update the FLMP (force structural maintenance plan), if the operational usage of the fleet is significantly different than the design assumption.
- To assign some missions known to be more or less damage rate to the aircraft with high or less fatigue consumption rate in period of time, to bring them closer to the average usage.

Normally there are many fatigue critical locations in airframe (called control points) determined from full-scale fatigue test to be tracked by the application. Compared with Legacy fighters, the number of control points has been increased dramatically. For example, EF-2000 has only 10 control points [4] while F-22 has 1408 points.

Of course, the more points to be tracked in the service, the more information about the statue of the aircraft will be got. However, too large a number of points would be too unwieldy to manage, because firstly it is a very huge task to calculate the fatigue damages for all control points, and secondly it is difficult to choice which result from one of locutions to be regarded as reference for aircraft structural life management.

Actually, for most of the fighter aircraft, the majority of fatigue-critical locations in an airframe are located around the wing attachment /center-fuselage, where structural loading is governed, to a significant degree, by g_z.hence, g_z can be used as a reliable means of estimating stress and therefore, fatigue damage [5].

It is a common way in practice to evaluate the severity between different usages such as comparing the fleet average spectrum with design spectrum or any individual aircraft load history. by using the corresponding load factor g_z exceedance curves. Enlightened from this simple and effective way, the goal of present study is to introduce a method for evaluating the general fatigue damage status for the concerned aircraft only by using the recorded g_z data.

2 Miner's Rule

Being one of the earliest emerged theories for fatigue damage calculation, Miner's rule has mostly been used in many western countries in their aircraft life monitoring practice such as Alphajet[8], Hawk, Tornado[3] and CF-18[6] etc. However, it has been proven by many studies that there are some shortcomings or limitations in the rule which may affect the accuracy of the calculation results [9].

The miner's rule can be expressed as

$$\lambda\sum\frac{n_i}{N_i}=Q \qquad (1)$$

Where λ =total life of the component, n_i = the number of cycles applied at a certain load amplitude, N_i = the number of cycles to failure at that load amplitude.

The error in the final calculations is mainly contributed by two factors.

Firstly the rule assumes that the damage caused by a cycle in a variable amplitude loading is equal to that of cycle of the same size under constant amplitude loading. "Damage" (D) related to one cycle is defined by the reciprocal 1/N obtained from the S-N curve of the material or component. The curve can be fitted by an exponential function, ie. $S^m\times N=\text{constant}$, so that it depends on the value of *m* (often called material constant). As the calculation results under different *m* are quite different, errors might be existed or even wrong conclusions might be obtained, if an unsuitable *m* is used during the damage calculation process. Unfortunately, it is quite difficult to choose the *m* value for the part concerned in practice, which is one of limitations in the Miner's rule.

Secondly, the rule assumes that failure would be occurred in theory, when the damage sum reaches unite (ie. Q=1), however, it has been observed that in most cases the Q is not equal to 1, which ranges from 0.01 to 10[10]. Obviously, Q has strong influence on the final calculation results. So that how to choose a right Q is other difficult task in the process of damage calculation by using Miner's rule.

3 The Method Based On Relative Miner's Rule

As the indefiniteness of Q can be overcome by using the relative miner's rule, the accuracy of the damage calculation is improved.

The basic idea of the relative Miner's rule is expressed by the formula [10]

$$\lambda_X=\frac{(\sum_{i=1}^{k}n_i/N_i)_Y}{(\sum_{i=1}^{j}n_i/N_i)_X}\lambda_Y. \qquad (2)$$

Where λ_X = predicted life for spectrum X, λ_Y = known fatigue life for spectrum Y. n_i = the number of cycles applied at the certain amplitude, and N_i = the number of cycles to failure at that amplitude.

In order to predict the life of aircraft component under various spectra, the author [11] developed a formula based on the relative Miner's rule which is given in (3)

$$\lambda_X=\frac{(\sum_{i=1}^{k}n_i\Delta g_{zi}{}^{m})_Y}{(\sum_{i=1}^{j}n_i\Delta g_{zi}{}^{m})_X}\lambda_Y \qquad (3)$$

Where $\Delta g_{zi} = (g_{zi-peak} - g_{zi-valley})$ is a certain range of the vertical load factor, λ_{Y} and $(n_i \Delta g_{zi}{}^m)_{\mathrm{Y}}$ are the life and total damage under design spectrum which have already been determined from the full-scale fatigue test known. Therefore $\lambda_{\mathrm{Y}} \times (\sum n_i \Delta g_{zi}{}^m)_{\mathrm{Y}}$ can be regarded as known constant C. Accordingly the formula (3) can be changed into (4)

$$\lambda_{\mathrm{X}} \times (\sum n_i \Delta g_{zi}{}^m)_{\mathrm{X}} = C \qquad (4)$$

Where λ_{X} and $(\sum n_i \Delta g_{zi}{}^m)_{\mathrm{X}}$ are the life and damage (D) that has consumed for the individual aircraft concerned under its own actual load history. It is can be seen that once D has been calculated, the λ_{X} can be got easily.

It must be noticed that the formula (3) is developed under following assumption that the local stresses in the majority locations are linear with the recorded g_z data which has been proven to be true for most types of fighters in China[11-12]. Therefore it is not necessary to convert g_z to local stress by using the formula (3) to calculate D.

For a certain component of the aircraft, if the corresponding material constant *m* is determined, the fatigue damage of the component under recorded g_z data can be easily calculated by using formula (4). Furthermore, when the designed life and total damage are known, the consumed life of the component can be got. However, there are many fatigue critical components in one type of airframe and as mentioned before, finding a suitable *m* for each of those components is very difficult. How can we use this formula to calculate the fatigue damage of each aircraft based on recorded g_z data and make comparisons among the fleet according to these calculations?

4 Study And Results

A study has been carried out by using more than 40396 hours of g_z data recorded form 71 aircraft belonged to two types of aircraft A and B The numbers of aircraft for the two types are 34 and 37. The main steps in this study are as following:

Firstly, process the g_z data of each flight landing by Rain-flow counting method to get all the pairs of $\Delta g_{zi} = (g_{zi-peak} - g_{zi-valley})$. Secondly calculates D_i (=$(\Delta g_{zi}{}^m)$) for all g_z pair. In order to examine the effect of *m* value, different constant *m* values have been used in the calculation varying from 3 to 10 respectively. Finally sum the all the D_i to get the D_L for whole landing, and sum all the D_L of same aircraft and divided by the corresponding flight hours to get general D rate for each aircraft.

The final results are given in fig.1 and fig.4. it can be seen that the D (fatigue rate) ~M (material constant) curves , each curve corresponding to one aircraft, are a group of parallel lines.

The higher the line is located in the Fig., the more the fatigue damage of the aircraft has accumulated. Therefore, from the D~M lines in the above figures, we can know the order of the fatigue damage accumulations consumed by each aircraft in the fleet. This information is very useful to aircraft life management. With consideration of the life already consumed and with prediction about further usage, the remaining service life of the aircraft can be determined and actions can be adopted, for example, those aircrafts with high damage rates can be allocated to fly less severe missions. By this way, the fatigue damage consumptions of the fleet can keep in a rational condition, so that the safety of the aircraft can be guaranteed, especially for those aircrafts with high damage consumptions, and the economical life the fleet is maximized while maintaining operational effectiveness.

Further calculations by using “D~M lines” method have been done systematically for these two types of aircraft in this paper. For aircraft of type A, fatigue damage of each aircraft were calculated by using flight data recorded during 1/3, 2/3 and whole flight training cycle respectively. For aircraft of type B, the same work were done by using recorded data during the period of less than 100 hours, between 100 and 200 hours and more than 300 hours respectively.

The results for the aircraft of type B are shown in fig.2~fig.4. Regression analysis were carried out for every group of D~M data and the liner correlation coefficient (R) and the slope (S) of each group are given in table 1, together with the mean value R and S, and the mean value of the standard deviations of R and S. It can be seen that with more flight data are used in the calculation, the mean value of R will be approach 1, and the standard deviations of R and S will be smaller, i.e. the linearity and parallelism of D~M lines are better.

5 Conclusion

It is shown from the present study that the fatigue damage rate (D) of each aircraft in the fleet is linear with material constant *m* (M) and all D~M lines are parallel to each other. In conclusion, the order of damage rate consumed by each aircraft in the fleet can not be changed no matter which *m* value (between 3~10) is used in the calculation. In practice we can choice any *m* (for example choice 4) for D calculation in order to make quantitative comparison. Therefore “D~M lines” method is a simple and effective tool to monitor and manage aircraft fatigue damage., for the difficulties of choosing fatigue critical components and finding corresponding *m* can be solved by using this method. .

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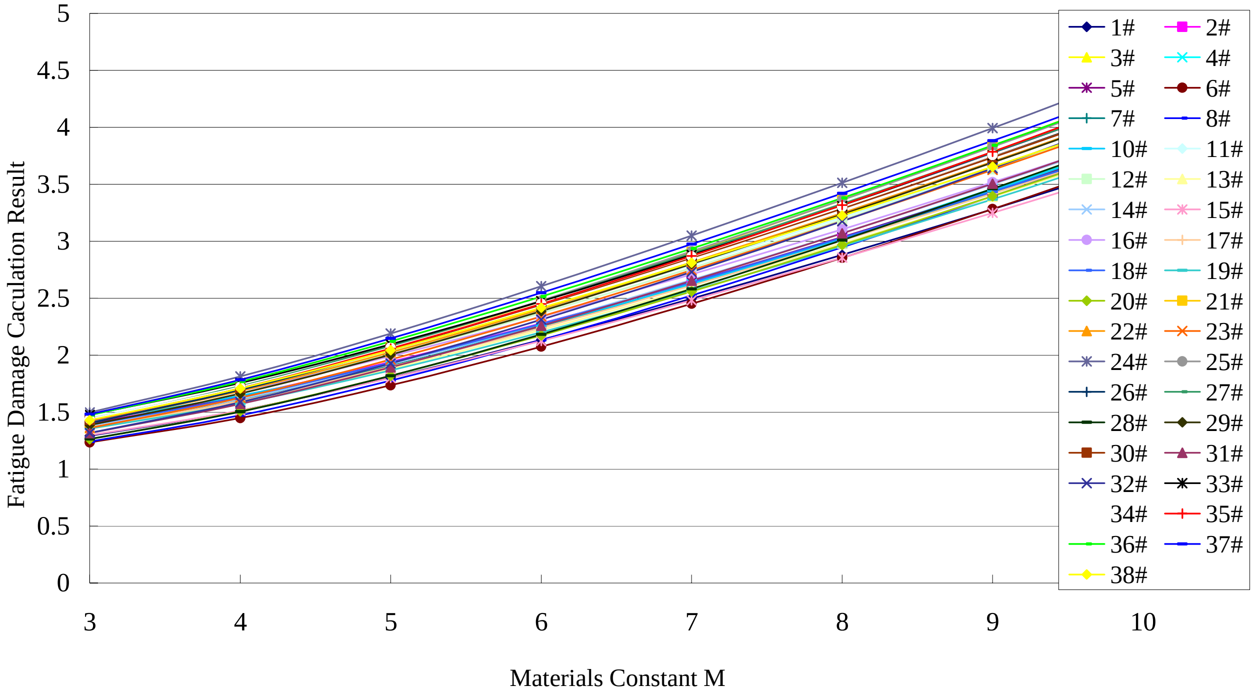

Fig.1. Fatigue Damage Calculated With Different Material Constant *M* (*M*=3~9) For Each Aircraft Of Type A

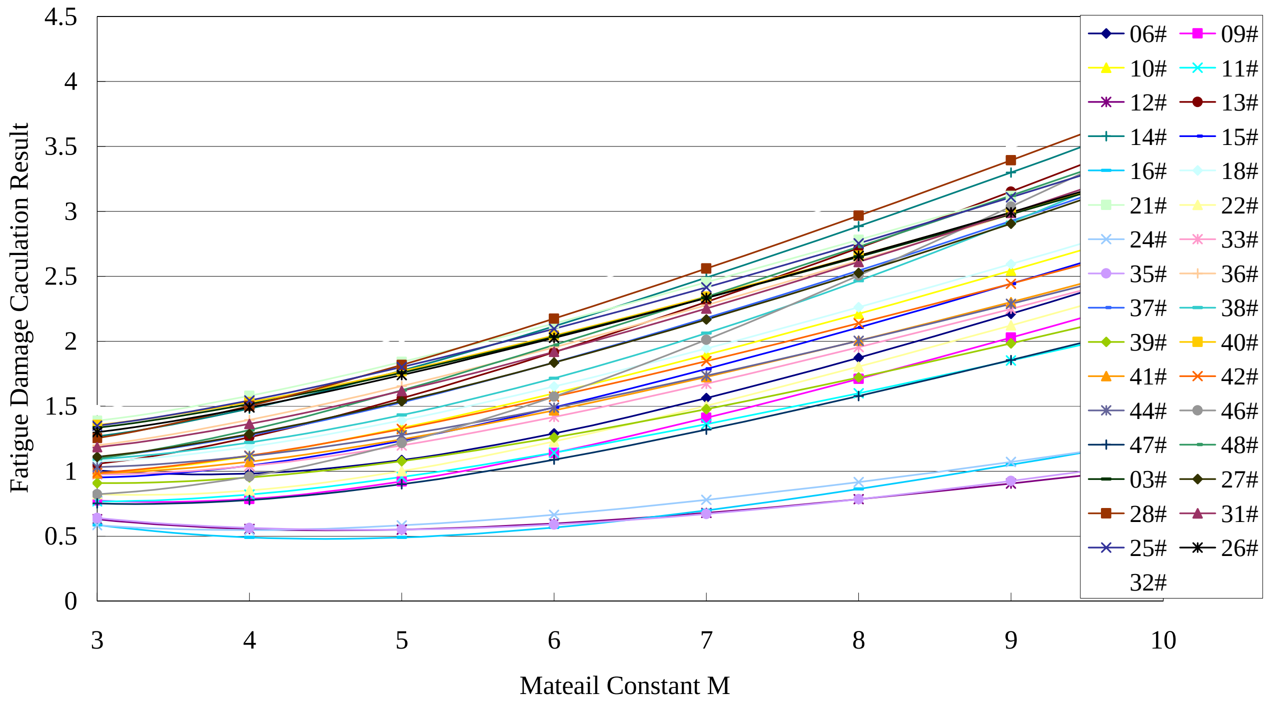

Fig .2. Fatigue Damage Calculation With Different Material Constant *M* for Each Aircraft Of Type B (less than 100 hour)

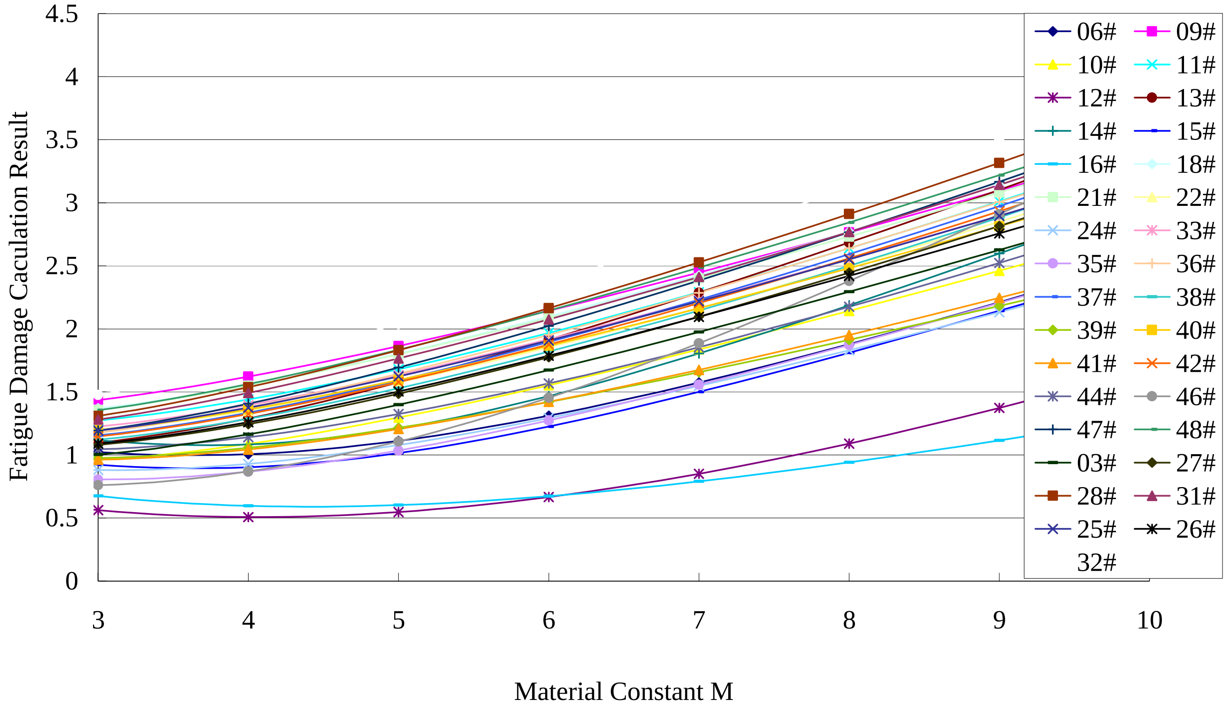

Fig 3 Fatigue Damage Calculations With Different Material Constant *M* For Each Aircraft Of Type A (Between 100 and 200 hours)

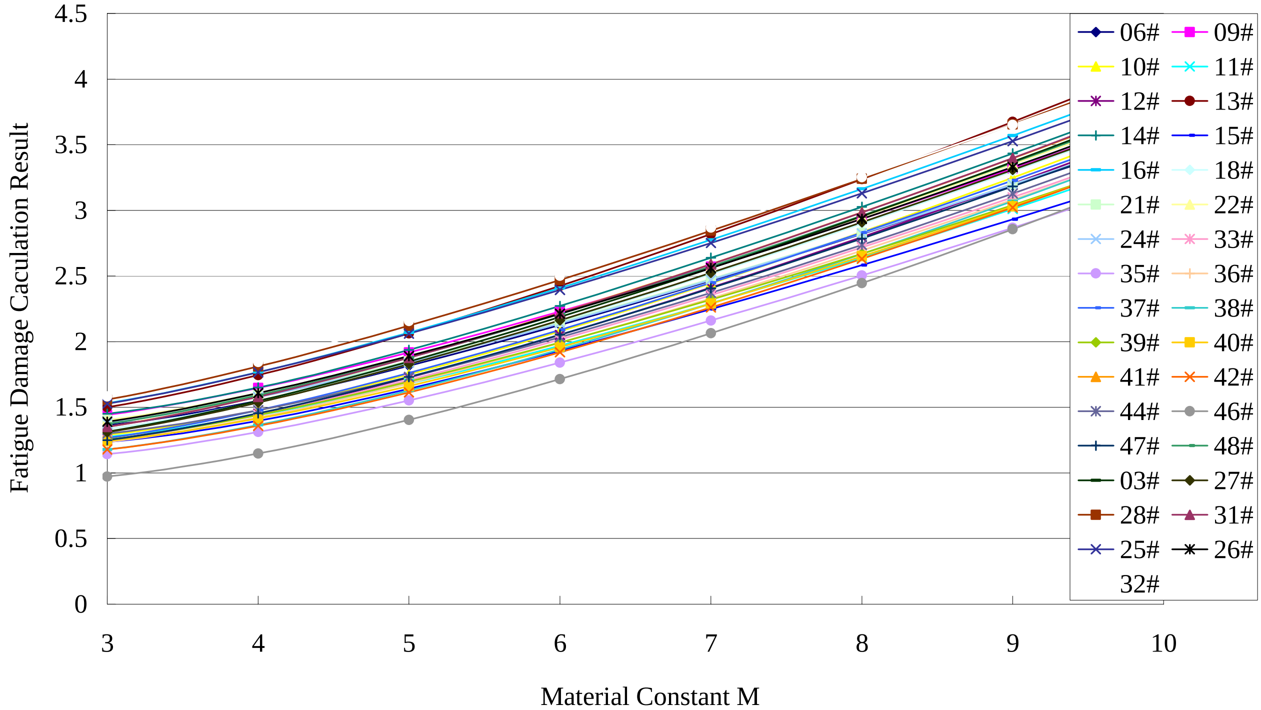

Fig .4. Fatigue Damage Calculation With Different Material Constant *M* for Each Aircraft Of Type B (More than 300 hours)

Table 1 Regression Analysis Results

Aircraft Type A							Aircraft Type B						
Tail No.	1/3 period		2/3 period		whole period		Tail No.	<100 hr		100<200<300 hr		>300 hr	
	R	**S**	**R**	**S**	**R**	**S**		**R**	**S**	**R**	**S**	**R**	**S**
1#	0.993	3.3733	0.9954	3.1304	0.9961	2.8458	06#	0.9668	3.9799	0.9676	4.0647	0.9957	3.0841
2#	0.9972	2.9988	0.9969	2.9185	0.997	2.8158	09#	0.9779	4.0301	0.9965	3.417	0.996	3.135
3#	0.996	2.7109	0.9961	2.6562	0.9962	2.7122	10#	0.9933	3.5447	0.9931	3.6871	0.994	2.8397
4#	0.9962	2.649	0.9959	2.8508	0.9956	2.7013	11#	0.9868	4.8864	0.9935	3.1956	0.9941	3.7843
5#	0.9948	2.9947	0.996	2.7652	0.9965	2.7719	12#	0.8872	12.279	0.9383	5.2763	0.9947	2.8715
6#	0.9932	3.0512	0.9932	2.6177	0.9947	2.7333	13#	0.9948	2.6695	0.9945	2.7863	0.9962	2.8733
7#	0.9954	2.7382	0.9953	2.8714	0.9963	2.7531	14#	0.9956	2.7746	0.9674	3.2481	0.9953	2.83
8#	0.9946	2.3624	0.9952	2.5772	0.995	2.61	15#	0.9891	3.6042	0.9697	3.9801	0.9949	3.2993
10#	0.9946	2.3624	0.9938	2.8435	0.9948	2.7748	16#	0.9042	7.8758	0.9109	8.5528	0.9968	2.7954
11#	0.9966	2.5742	0.9972	2.5502	0.9969	2.5987	18#	0.9914	3.5915	0.9949	3.168	0.9952	3.0157
12#	0.9949	3.1376	0.9958	2.515	0.9962	2.5831	21#	0.9972	3.295	0.996	3.2811	0.9954	3.1355
13#	0.9935	2.9195	0.9942	2.8641	0.9964	2.7873	22#	0.9817	3.9661	0.993	3.356	0.9951	3.0351
14#	0.9947	2.7584	0.9958	2.6638	0.9961	2.6683	24#	0.9497	9.0996	0.9838	4.1708	0.9952	3.5271
15#	0.9968	2.9306	0.9962	2.9687	0.9962	2.9046	33#	0.9869	4.1622	0.9953	3.3616	0.9956	3.0967
16#	0.995	2.7102	0.9956	2.8288	0.9968	2.7427	35#	0.8662	11.061	0.9848	3.7503	0.9941	3.2304
17#	0.9958	2.7353	0.9956	2.7933	0.9964	2.7648	36#	0.9962	3.186	0.9962	3.0974	0.9954	3.1953
18#	0.9968	3.008	0.9965	2.8896	0.997	2.7899	37#	0.994	3.0587	0.9945	3.0747	0.9948	3.0068
19#	0.9936	2.751	0.9956	2.7548	0.9958	2.8077	38#	0.9843	2.8948	0.9928	3.1368	0.9938	2.9408
20#	0.9968	3.0303	0.9964	2.779	0.9964	2.663	39#	0.9833	4.8423	0.9898	4.4833	0.9929	3.6224
21#	0.9959	2.8018	0.9968	2.4949	0.9974	2.3607	40#	0.9961	3.4631	0.9953	3.476	0.9951	3.4322
22#	0.9972	2.9319	0.996	2.5377	0.9972	2.4981	41#	0.9897	4.0963	0.9883	4.1772	0.9928	3.3223
23#	0.9965	2.8421	0.9956	2.7476	0.9969	2.518	42#	0.9942	3.8252	0.9944	3.1258	0.9944	3.1144
24#	0.9961	2.7082	0.9957	2.5285	0.9979	2.3085	44#	0.9891	4.2894	0.9872	3.608	0.9936	3.0373
25#	0.9962	2.7677	0.9972	2.4238	0.9978	2.3787	46#	0.9854	2.3953	0.9828	2.4339	0.9926	2.927
26#	0.9959	2.6084	0.9964	2.543	0.9976	2.4201	47#	0.98	4.6412	0.9959	2.864	0.9963	2.8653
27#	0.9967	2.8269	0.9957	2.749	0.9978	2.454	48#	0.9971	2.8138	0.9963	3.0433	0.9957	2.8107
28#	0.9953	2.6045	0.995	2.7031	0.9956	2.5687	03#	0.9965	3.4532	0.9952	3.4575	0.9969	3.159
29#	0.9949	2.7559	0.9966	2.519	0.9971	2.4811	27#	0.994	3.1023	0.9936	3.1986	0.9933	3.4067
30#	0.9956	2.9223	0.9964	2.6641	0.9975	2.4906	28#	0.9967	2.6634	0.9963	2.827	0.9976	2.6997
31#	0.9958	2.9175	0.9962	2.6853	0.9968	2.6027	31#	0.9944	3.0961	0.9964	3.0497	0.996	3.0867
32#	0.9943	2.6375	0.9966	2.5783	0.9965	2.4461	25#	0.9962	3.2216	0.9958	3.3164	0.997	2.9662
33#	0.9969	3.1007	0.9961	2.6353	0.9974	2.5172	26#	0.9966	3.3568	0.9958	3.3824	0.9957	3.0465
34#	0.9952	2.7125	0.997	2.5735	0.9974	2.4737	32#	0.9979	2.8498	0.998	2.8484	0.9979	2.7829
35#	0.9937	2.3885	0.9961	2.4197	0.997	2.4201	**MV**	0.9797	4.3051	0.9868	3.5726	0.9952	3.0902
36#	0.9962	3.0798	0.9964	2.5223	0.9975	2.4247	**SD**	0.0321	2.3439	0.0183	1.0533	0.0013	0.2551
37#	0.9945	2.7152	0.9959	2.5034	0.9979	2.3995							
38#	0.996	2.9594	0.9967	2.7529	0.9979	2.5873							
MV	0.9955	2.8129	0.9959	2.687	0.9967	2.6048							
SD	0.0011	0.2192	0.0009	0.1649	0.0009	0.161							

Note: **S**—Slope, **R**—Correlation Coefficient, **MV**—Mean Value, **SD**—Standard Deviation