Experiments on the Start and Stop of Windmill- and Cup-Anemometers with Particular Reference to Their Over-Estimation Factors

by

M. Sanuki

Meteorological Research Institute

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Abstract

Three- and four-bladed windmill-anemometers and cup-anemometers are started from rest in the wind tunnel and are also stopped from rotation in a still air, and their responses are compared with one another. The static torque coefficients are calculated from the observation of rotational speed versus time to be used in SCHRENK's parameter. SCHRENK's over-estimation factors for both anemometers are evaluated into a single chart for rectangular wind waves. For sinusoidal wind waves, graphical solution of the equation of motion is carried out, from which the over-estimation factor is computed and compared with experiment due to DEACON. The phase lag is also obtained into a chart.

1. Object of the present experiment and analysis

After we have conducted a systematic investigation of the design of windmill anemometers [1], we have remarked a somewhat appreciable difference between the observed wind course with it and that with the ordinary cup-anemometer.

To clarify the cause, experiments on the stop of both types are carried out in the wind tunnel and in a still air. The anemometers are started from rest in the tunnel flow and also they are stopped from rotation in a still air. From these so-called dynamic experiments the static torque coefficients are calculated assuming some equations of motion. The analysis is further pushed on to calculate the over-estimation factor. For this purpose the above-mentioned simple experiments are found to play an unexpectedly important role.

2. The start of windmill-anemometer

The equation of motion of a windmill-anemometer when started by a uniform wind speed can be written in the form

$$(1) \quad \begin{cases} I \frac{d\omega}{dt} = c, & (0 \leq \omega \leq \omega_{\infty/2}) \\ I \frac{d\omega}{dt} = c' - c''\omega, & (\omega_{\infty/2} \leq \omega \leq \omega_{\infty}) \end{cases}$$

where I is the moment of inertia with respect to the axis of the anemometer, ω the angular velocity, t time, c , c' and c'' are constants, and ω_{∞} is the final angular velocity corresponding to the wind speed V . It is seen the torque of a windmill changes against the rotation ratio $\omega R/V$ (R is the windmill radius) for blade angles near 60° at 75% radius as shown in Fig. 1, (half-stalled condition, Reference 1), and the constants c , c' and c'' may be written as

$$(2) \quad \begin{cases} c = c_{d_0} \frac{1}{2} \rho V^2 \cdot \pi R^2 \cdot R, \\ c' = 2c, \\ c'' = 2c/\omega, \end{cases}$$

where c_{d_0} is the dimensionless torque coefficient, ρ the air density and V the wind speed.

Equation (1) can easily be integrated and we get

$$(3) \quad \begin{cases} \omega = \frac{c}{I} t, & (0 \leq \omega \leq \omega_{\infty/2}), \\ \omega = \frac{1}{c''} \left\{ c' + (c'\omega_0 - c') e^{-\frac{c''}{I} t} \right\}, & (\omega_{\infty/2} \leq \omega \leq \omega_{\infty}), \end{cases}$$

where ω_0 is the value of ω at $t=0$. From the second solution of (3) we see $\omega = c'/c'' = \omega_{\infty}$ at $t = \infty$.

If a windmill is started from rest in a wind of uniform speed of V , and ω is observed at each time interval, the constants c and c' (also c'') can be calculated and the starting torque coefficient c_{d_0} may be obtained.

In Fig. 2 are shown the experiments conducted for Speedovane with three- and four-blader windmills (their forms and dimensions are given in Reference [2]) in the 1.5-meter wind tunnel of the Meteorological Research Institute. It is observed that the four-blader is

Fig. 2. Start of Speedovane in various wind speeds, and calculated starting torque coefficient (M. R. I. wind tunnel).

superior to the three-blader in start, and the final indication is obtained in 70%

Fig. 1. Torque coefficient of half-stalled windmill ($\omega_1 \equiv \omega_{\infty}$).

of time of that for the latter. The calculated starting torque coefficient c_{a_0} is correspondingly, about 15%, larger for the four-blader than the three-blader.

The starting-torque coefficient c_{a_0} is, on the other hand, tested in the wind tunnel as shown in Fig. 3. In this test the three-blader gives larger values of c_{a_0} than the four-blader by about 15–20%. This fact is somewhat questionable and the reason is not yet well explored. The moment of inertia I is 0.000324 kgms² for the three-blader and 0.000273 kgms² for the four-blader, but they do not come into the calculation of c_{a_0} . The developed surface area A is the same for both windmill blades, given by

Fig. 3. Static torque coefficient of Speedovane. (Windmill diameter 350 mm, M. R. I wind tunnel.)

Fig. 4. Start of cup-anemometer in various wind speeds, and calculated starting torque coefficient (M. R. I. wind tunnel).

$$(4) \quad A = p \int_{-\pi/p}^{\pi/p} \frac{1}{2} r^2 d\theta = R^2,$$

as the plan-form of the windmill blades is designed after the following formula in polar coordinates (r, θ)

$$(5) \quad r^2 = R^2 \cos p\theta,$$

where p is the number of blades and $R = 0.175$ m in the present case.

3. The start of cup-anemometer

The equation of motion of a cup-anemometer in start by a uniform wind speed V is written [3] as

$$(6) \quad I \frac{d\omega}{dt} = c' - c''\omega,$$

where c' and c'' are constants. The solution has the same form as the second type of Equation (3). The constants can now be written in the form

$$(7) \quad \begin{cases} c' = c_{a_0} \cdot \frac{1}{2} \rho V^2 \cdot p\pi R_0^2 \cdot R, \\ c'' = c'/\omega_{\infty}, \end{cases}$$

where p is the number of cups, c_{a_0} the dimensionless starting torque coefficient, R_0 the cup radius, R the cup center radius and other

notations are the same as before. In the present case, $I=0.00139 \text{ kgms}^2$, $p=4$, $R_0=0.04 \text{ m}$, $R=0.14 \text{ m}$. The wind tunnel test results are illustrated in Fig. 4. The start is found to be most favourable when the cup arm is inclined at 45° to the wind direction in its initial stage, but the time necessary to attain the final rotating speed does not differ much for the initial cup positions. In the figure an example of 30° inclination is shown.

It is seen that the cup-anemometer requires about three times as much time as Speedovane with four-bladed windmill to obtain the same final rotating speed. The values of c_{d_0} increase with increasing ω showing the effect of bearing friction. Moreover, c_{d_0} increases with V , which fact can be explained by the change of flow pattern with Reynolds number. American wind tunnel test on four-cup wheel [4] gives $0.59\sim 0.56$ for $V=9\sim 15 \text{ m/s}$, $R_0=0.508 \text{ m}$, $R=0.236 \text{ m}$, which values are in good conformity to our results for lower V .

4. The stop of windmill-anemometer

The equation of motion of a rotating windmill-anemometer in a still air may be written in the form

$$(8) \quad I \frac{d\omega}{dt} = -c\omega^2,$$

where c is a constant and other notations are the same as before. c can be written as

$$(9) \quad c = C_{Q_0} \rho n^2 D^5 / \omega_2 = \frac{8}{\pi^2} C_{Q_0} \rho R^5,$$

where C_{Q_0} is the dimensionless static torque coefficient used in the experimental expression of propellers, n the number of revolution, and D the windmill diameter.

In a still air the Speedovane is brought to rest from an initial rotation, and the angular velocity ω is observed for each time interval as illustrated in Fig. 5, where $\omega=1 \text{ rad/s}$ corresponds to about $V=0.30 \text{ m/s}$. It is seen that the three-blader needs $100\sim 200\%$ more time than the four-blader before it stops. From the observations the values of c and

Fig. 5. Stop of Speedovane with various initial angular velocities in a still air.

therefore C_{q_0} are calculated from the solution of Equation (8), viz.,

$$(10) \quad \omega = \frac{I\omega_0}{c\omega_0 t + I},$$

where ω_0 is the initial angular velocity. The values of C_{q_0} rapidly increase with decreasing ω indicating the bearing friction effect.

The order of C_{q_0} thus obtained can be compared with the experimental results for propellers. The three-bladed propeller 5868-9 [5] gives $C_{q_0}=0.087$ for blade angle 60° (i.e., the blade angle of the Speedovane blades) at 75% radius. If the torque is assumed to be proportional to the blade width we get $C_{q_0}=0.27$ for the Speedovane three-blader which value is in good coincidence with the present experimental result for higher rotational speed, as seen in Fig. 5 a.

5. The stop of cup-anemometer

The equation of motion of a rotating cup-anemometer in a still air is written in the form

$$(11) \quad I \frac{d\omega}{dt} = -c\omega^2,$$

where c is a constant and other notations are the same as before. c can be expressed as

$$(12) \quad c = C_D \cdot \frac{1}{2} \rho V^2 p \pi R_0^2 \cdot R,$$

where p is the number of cups, C_D the dimensionless drag coefficient of the cup, R_0 the cup radius, and R the cup center radius.

The cup-anemometer is brought to rest in a still air from an initial rotational speed ω_0 ($\omega=1$ rad/s corresponds to $V = \text{ca. } 0.37$ m/s), and from Equation (11) the values of c or C_D are calculated as illustrated in Fig. 6. The cup-anemometer requires a remarkably longer time than the Speedovane before it is brought to rest.

The order of C_D thus obtained may be checked by experimental results. An American experiment [4] shows that the drag coefficient of a hemispherical cup as $C_D=1.4$. The present experiment gives about $C_D=3.5$. The difference might be

Fig. 6. Stop of cup-anemometer with various initial angular velocities in a still air.

attributed to the aerodynamic interference or other causes.

The cup type requires much more time than the windmill type before it stops. For each type the time taken before it stops is nearly constant in spite of the initial angular velocity differences.

6. Frictional effect

The bearing friction is included in the constants in the equations of motion. The static friction torque is of the order of 10 grcm for the windmill type and 2 grcm for the cup type. Therefore the effect is never negligible except for higher values of $d\omega/dt$ and the obtained values of constants comprise both aerodynamic and mechanical effects.

The friction decreases as angular velocity increases. If we consider the static friction torque as the upper limit of mechanical effect, it influences the total accelerating or decelerating torque by more than 10% for the range $d\omega/dt \leq 0.84/s^2$ for the three-blader windmill type, $d\omega/dt \leq 1.09/s^2$ for the four-blader, and $d\omega/dt \leq 0.14/s^2$ for the cup type. And the mechanical effect plays the chief role for the range $d\omega/dt \leq 0.084/s^2$ for the three-blader, $d\omega/dt \leq 0.109/s^2$ for the four-blader, and $d\omega/dt \leq 0.014/s^2$ for the cup type. Naturally these limits seem to be too severe for actual cases, but as no reasonable relations are yet found between frictional torque and angular velocity, the above values represent only cautious margins.

7. Over-estimation of anemometer indication

Next we shall consider the over-estimation of anemometer indication in general. We assume the wind speed fluctuation as shown in Fig. 7 (rectangular wind waves), where V_0 is the mean wind speed, ΔV the amplitude and T the period.

The accelerating torque coefficient of anemometer is also assumed as

$$(13) \quad c_a = \text{torque} / \frac{1}{2} \rho V^2 \cdot \pi R^2 \cdot R = 2c_{a_0} - 2c_{a_0} \lambda_0 \frac{\omega R}{V},$$

for the windmill type, neglecting the friction. c_a is the static torque coefficient for the speed ratio $V/\omega R = \infty$, and the speed ratio in equilibrium $\lambda_0 = V_0/\omega_0 R$, ω_0 being the rotational speed corresponding to V_0 .

For the cup type we take

$$(14) \quad c_a = \text{torque} / \frac{1}{2} \rho V^2 \cdot p \pi R^2 \cdot R = c_{a_0} - c_{a_0} \lambda_0 \frac{\omega R}{V},$$

where c_{a_0} is the static torque coefficient.

The braking torque coefficient is usually written for the windmill type in the form

Fig. 7. Wind fluctuation.

$$(15) \quad k_a = \text{torque} / \frac{1}{2} \rho \omega^2 R^2 \cdot \pi R^2 \cdot R = c_a \left(\frac{V}{\omega R} \right)^2.$$

The same relation holds also for the cup type if we define $k_a = \text{torque} / \frac{1}{2} \rho \omega^2 R^2 \cdot p \pi R_0^3 \cdot R$. By this transformation Equation (13) becomes

$$(16) \quad k_a = 2c_{a0} \left(\frac{V}{\omega R} \right)^2 - 2c_{a0} \lambda_0 \frac{V}{\omega R},$$

for the windmill type if we wish continuous variation of torque coefficient near equilibrium state at $c_a = 0$ and $V/\omega R = V_0/\omega_0 R = \lambda_0$. For the cup type we get

$$(17) \quad k_a = c_{a0} \left(\frac{V}{\omega R} \right)^2 - c_{a0} \lambda_0 \frac{V}{\omega R}.$$

Fig. 8 illustrates c_a versus $\omega R/V$ and k_a versus $V/\omega R$ together with the experimental results on cup-anemometers due to SCHRENK [7].

Fig. 8. Approximate expressions of cup-anemometer torque coefficients.

The rotational speed ω_{2n-1} corresponding to the odd $(2n-1)$ -th half wind wave end can be written from Equation (3) after some calculations as

$$(18) \quad \frac{\omega_{2n-1}}{\omega_0} = 1 + S + 2Se^{-2K\pi} \left\{ \frac{1 - e^{-2(n-1)K\pi}}{1 - e^{-2K\pi}} \right\} \{1 - e^{K\pi(1-S)}\} - Se^{-K\pi(2n-1+S)},$$

where $S = \Delta V/V_0$, and $n = 1, 2, 3, \dots$.

The rotational speed ω_{2n} corresponding to the even $2n$ -th ($n = 1, 2, 3, \dots$) half wind wave end is obtained in the similar manner as

$$(19) \quad \frac{\omega_{2n}}{\omega_0} = 1 - S - 2Se^{-2K\pi} \left\{ \frac{1 - e^{-2nK\pi}}{1 - e^{-2K\pi}} \right\} \{1 - e^{K\pi(1+S)}\} + Se^{-2nK\pi}.$$

The over-estimation factor corresponding to the odd $(2n-1)$ -th half wind wave (N.B. not the accumulative over-estimation but a single one for the half wave concerned) is defined and calculated as

$$(20) \quad \begin{aligned} Z_{t, 2n-1} &= \left\{ \frac{2}{T} \int_0^{T/2} \omega dt - \omega_0 \right\} / \omega_0 \\ &= S + \frac{1}{K\pi(1+S)} \left\{ \frac{\omega_{2n-2}}{\omega_0} - (1+S) \right\} \{1 - e^{-K\pi(1+S)}\}, \end{aligned}$$

where t denotes time, and K is SCHRENK's parameter defined by

$$(21) \quad K = 2c_{d0}\lambda_0\rho V_0 TR^4/4I,$$

for the windmill type and

$$(22) \quad K = pc_{d0}\lambda_0\rho V_0 TR_0^2 R^2/4I,$$

for the cup type. It is to be noted here that pc_{d0} and λ_0 are used in the same meaning as SCHRENK's aerodynamic coefficients α and $\sqrt{\beta/\alpha}$.

Similarly for the even $2n$ -th half wind wave we have

$$(23) \quad Z_{t, 2n} = -S + \frac{1}{K\pi(1-S)} \left\{ \frac{\omega_{2n-1}}{\omega_0} - (1-S) \right\} \{1 - e^{-K\pi(1-S)}\}.$$

The over-estimation factor for the n -th complete wave should be taken as $(Z_{t, 2n-1} + Z_{t, 2n})/2$.

If n is taken to be infinity the rotational speed tends to

$$(24) \quad \lim_{n \rightarrow \infty} \frac{\omega_{2n-1}}{\omega_0} = 1 + S + 2Se^{-2K\pi} \left\{ \frac{1 - e^{-K\pi(1-S)}}{1 - e^{-2K\pi}} \right\},$$

for the odd half wind wave end and to

$$(25) \quad \lim_{n \rightarrow \infty} \frac{\omega_{2n}}{\omega_0} = 1 - S - 2Se^{-2K\pi} \left\{ \frac{1 - e^{-K\pi(1+S)}}{1 - e^{-2K\pi}} \right\},$$

for the even half wind wave.

The over-estimation factor becomes in each case

$$(26) \quad \lim_{n \rightarrow \infty} Z_{t, 2n-1} = S - \frac{2S}{K\pi(1+S)(1 - e^{-2K\pi})} \{1 - e^{-K\pi(1+S)}\} \{1 - e^{-K\pi(1-S)}\},$$

for the odd half wind wave, and

$$(27) \quad \lim_{n \rightarrow \infty} Z_{t, 2n} = -S + \frac{2S}{K\pi(1-S)(1 - e^{-2K\pi})} \{1 - e^{-K\pi(1+S)}\} \{1 - e^{-K\pi(1-S)}\},$$

for the even half wind wave.

The over-estimation factor for the one complete wind wave after infinite series of waves is finally given by

$$(28) \quad Z_t = \lim_{n \rightarrow \infty} \frac{Z_{t, 2n-1} + Z_{t, 2n}}{2} = \frac{2S^2 \{1 - e^{-K\pi(1+S)}\} \{1 - e^{-K\pi(1-S)}\}}{K\pi(1-S^2)(1 - e^{-2K\pi})}.$$

The value of Z_t thus defined has the same meaning as that adopted by SCHRENK. As limiting cases we have

$$(29) \quad \lim_{K \rightarrow 0} Z_t = S^2,$$

and

$$(30) \quad \lim_{K \rightarrow \infty} Z_t = 0.$$

In Fig. 9 the over-estimation factor Z_t is illustrated against K . Comparing this chart with that given by SCHRENK we immediately notice that our calculated values of Z_t are markedly larger than those of SCHRENK. This discrepancy arises

Fig. 9. Over-estimation factor for rectangular wind waves.

(32)

$$c_a = c_{a0} - c_{a0} \lambda_0^2 \left(\frac{\omega R}{V} \right)^2,$$

or

(33)

$$k_a = c_{a0} \left(\frac{V}{\omega R} \right)^2 - c_{a0} \lambda_0^2,$$

we get, in case of $K=0$ and rectangular wave,

(34)

$$Z_t = \sqrt{1+S^2} - 1.$$

The over-estimation factors for $K=0$ obtained from Equations (29), (31) and (34) together with SCHRENK's calculation for sinusoidal wind fluctuation

$$(35) \quad Z_t = \sqrt{1+S^2/2} - 1$$

are illustrated in Fig. 10.

The value of Z_t differs much according to the form of anemometer torque coefficient formula assumed, and also according to the mode of wind fluctuation, but the reasonable margin of Z_t seems to exist a little higher (SCHRENK employed a factor 1.4) than the lowest curve in Fig. 10. If, therefore, we modify the curves in Fig. 9 by multiplying with some factor according to Fig. 10, we

from two causes. One is the assumption of anemometer torque coefficient expressed in Equation (14), and the other is the assumption of rectangular wind waves, compared with sinusoidal ones in case of SCHRENK.

If we employ for $K=0$, under the assumption of Equation (14), the sinusoidal waves

$$\frac{V}{V_0} = 1 + S \sin 2\pi \frac{t}{T},^*$$

and if we write $\omega/\omega_0 = 1 + Z_t$ where Z_t is now a constant independent of time, we get

$$(31) \quad Z_t = \frac{S^2}{2},$$

from the condition

$$\int_0^T (\text{anemometer torque}) dt = 0.$$

Further if we assume after SCHRENK, instead of Equation (14),

Fig. 10. Over-estimation factors for $K=0$.

* S corresponds to S of SCHRENK.

shall be able to obtain a chart quite similar to that given by SCHRENK.

Before concluding this section, one more fact should be pointed out. The foregoing over-estimation factor is concerned with the terminal state after infinite

Fig. 11. Over-estimation factor for the state after finite number n of wind waves. (Rectangular wind waves, cf. Fig. 9).

series of wind waves. But Equations (20) and (23) stand for cases of a finite number of waves. The over-estimation factor $(Z_{t,2n-1} + Z_{t,2n})/2$ is calculated and illustrated in Fig. 11 for $n=5, 10$ and ∞ for rectangular wind waves without any correction. The effect of the number of waves is marked only for lower region of K which will be realized by the anemometer in case of slow wind speed with high frequency.

For the same reason the over-estimation is more pronounced for lower air density. Mountain stations will suffer more from the overrunning of the anemometer than stations situated on the plain.

8. Graphical solution of the equation of motion

SCHRENK has solved by an approximate method the equation of motion of a cup type

$$(36) \quad I \frac{d\omega}{dt} = \frac{1}{2} c_a \rho V^2 \cdot p \pi R_0^2 \cdot R,$$

where c_a is given in Equation (32). This equation can be written as

$$(37) \quad \frac{d\omega_1}{dt_1} = 2\pi K \{(1 + S \sin 2\pi t_1)^2 - \omega_1^2\},$$

where $\omega_1 = \omega/\omega_0$, $t_1 = t/T$, and the sinusoidal variation of V is assumed as before. Equation (37) is non-linear and the present author solved it by the isocline method described in Reference [8]. An example of the graphical solution for $K=1$, $S=0.5$ is shown in Fig. 12. The variation of the anemometer speed $\omega_1 = \omega/\omega_0$ against the time $t_1 = t/T$ is almost sinusoidal with a certain phase lag from the wind wave.

Fig. 12. Computed rotational speed of anemometer for sinusoidal wind waves ($K=1$, $S=0.5$).

Fig. 13. Computed over-estimation factor for sinusoidal wind waves compared with the experiment due to DEACON.

The over-estimation factor Z_t defined in Equation (28) after a certain number of waves is computed in Fig. 13, together with that calculated by SCHRENK, and experiment by DEACON [9]. The calculation by the present author is multiplied with the factor 1.4 for the same reason as given by SCHRENK. Better coincidence with the experiment for quasi-sinusoidal wind waves is found than the calculation due to SCHRENK, which is somewhat arbitrary interpolation between two limiting cases of K . According to this result, SCHRENK seems to have employed the factor 1.4 with fairly acceptable reason except the intermediate ambiguity in his calculation.

Fig. 14. Computed phase lag chart.

Further the phase lag defined in Fig. 12 is computed as illustrated in Fig. 14. The limiting case for $S=0$ is also added, for which a quarter-period phase lag is to be expected for $K=0$.

(38)
$$K = c_{a_0} \lambda_0 \rho V_0 T R^4 / 4I$$

On this occasion it is to be stressed that the present discussion applies equally to the windmill-anemometer if we write

instead of Equation (21), based on the assumption of parabolic variation of torque coefficient.

In both cases of cup and windmill types the experimental determination of c_{a_0} described in Articles 2 to 5 affords simple and reasonable basis to the calculation of SCHRENK's parameter K . The evaluation of c_{a_0} was based on linear variation of

torque coefficient but may safely be applied also to SCHRENK's cases.*

On the whole, the over-estimation of the windmill-anemometer seems to be far less than that of cup type, as the value of K for the former ranges from 0.020 to 200 for $V_0=1$ m/s, $T=1$ s and $V_0=100$ m/s, $T=100$ s ($c_{d_0}=0.10$, $\lambda_0=1.69$, $\rho=1/8$ kg m⁻⁴s², $R=0.175$ m, $I=0.000273$ kg m s² for four-blader), whereas for the latter $K=0.0030$ to 30 also for the same legends ($c_{d_0}=0.40$, $\lambda_0=2.65$, $R_0=0.04$ m, $R=0.14$ m, $I=0.00139$ kg m s², $p=4$) respectively. And further, if the windmill type should follow the wind with less than 5% over-estimation and also 5% phase lag even in the wind waves of $V_0=1$ m/s, $T=1$ s, the moment of inertia must be reduced to 1/50 of the present value (cf. Figs. 13 and 14).

9. Conclusions

From the experimental results are deduced the following conclusions:

- 1) The overrunning is more pronounced than the underrunning both for windmill- and cup-anemometer.
- 2) The windmill type is superior to the cup type with respect to the response.
- 3) The four-blader windmill is superior to the three-blader in the same sense.

From the theoretical calculations are to be shown:

- 4) Linear expression of the anemometer accelerating torque coefficient gives, for square wind waves, much larger over-estimation factor than that given by SCHRENK for sinusoidal wind waves.
- 5) The effect of finite number of wind waves is only conspicuous for smaller values of SCHRENK's parameter.
- 6) Graphical solution of the equation of motion gives somewhat different values of over-estimation factor from those given by the approximate method due to SCHRENK. As regards the agreement with the experiment by DEACON, the former values are better.
- 7) The phase lag is larger for smaller amplitudes of the wind fluctuations.
- 8) The start and stop method affords simple and reasonable determination of aerodynamic factors in SCHRENK's parameter.

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* Of course, the direct integration of Equation (37) is possible in case of start and stop, which gives more reasonable value of K .

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