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The Evaluation of Downwash at Large Spanwise Distances from a Vortex Lattice

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The Evaluation of Downwash at Large Spanwise Distances from a Vortex Lattice

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Summary.—This note explains an improved numerical method of evaluating the contributions to the downwash at moderate or large spanwise distances from a vortex lattice. By allowing freedom of choice of the chordwise positions of the discrete vortices of the lattice, it is possible to select three definite chordwise positions and strengths of vortices at each of these positions dependent on the chordwise pressure distribution, so as to determine the downwash with good accuracy for three particular pressure distributions proportional to cot $\frac{1}{2}\theta$, sin θ and sin 2θ.

The corresponding chordwise loading factors have also been evaluated for deflected flaps.

1. *Introduction.*—In the calculation of wing loading by vortex-lattice theory (Falkner, 1943)[1], the pressure difference across the wing is assumed to be of the general form

$$(p_b - p_a) = \rho V k = 8\rho V^2 \cdot \frac{s}{c}\left[F_0 \cot \tfrac{1}{2}\theta + F_1 \sin\theta + F_2 \sin 2\theta\right], \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where s is the semi-span of the wing,

c is the local chord of the wing,

F_0, F_1, F_2 are functions of spanwise position y,

θ is related to the distance x downstream of the local leading edge by $x = \frac{1}{2}c(1 - \cos\theta)$.

The corresponding downwash is evaluated as the sum of contributions from areas bounded in the spanwise direction. Each of these contributions is calculated on the assumption that the vortex strength k is independent of y over the area. Such vorticity is truly represented by a distribution of horseshoe vortices of the given spanwise extent and strength k per unit length in the chordwise direction.

If s_1 is the semi-span of a particular area and x and y are measured from the leading edge of the centre-section of that area, then the downwash velocity at a point (x_1, y_1) due to the horseshoe vorticity is

$$w = \frac{1}{4\pi s_1}\int_0^c F(X,Y) k \, dx\,, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

where
$$X = \frac{x - x_1}{s_1}$$

$$Y = \frac{y_1}{s_1}$$

$$F(X,Y) = \left(\frac{1}{Y+1} - \frac{1}{Y-1}\right) - \left\{\frac{[X^2 + (Y+1)^2]^{1/2}}{X(Y+1)} - \frac{[X^2 + (Y-1)^2]^{1/2}}{X(Y-1)}\right\}.$$

2. *Approximate Method of Evaluating w.*—It is required to find a simple numerical method of evaluating w, when Y is large enough.

On expansion in powers of $\frac{1}{Y}$,

$$F(X,Y) = -\frac{2}{Y^2}\left(1 + \frac{1}{Y^2} + \frac{1}{Y^4} + \ldots\right) + \frac{2X}{Y^3}\left(1 + \frac{2}{Y^2} + \frac{3}{Y^4} + \ldots\right)$$
$$+ \frac{X^3}{Y^5}\left(1 + \frac{5}{Y^2} + \ldots\right) + \frac{3X^5}{4Y^7}(1 + \ldots) + \ldots .$$

Thus on writing

$$F(X,Y) = G_0(Y) + G_1(Y) . X + G_2(Y) . X^3 ,$$

the highest neglected term is $\frac{3X^5}{4Y^7}$.

Since $$X = \frac{x - x_1}{s_1} = \frac{c}{2s_1}(1 - \cos\theta) - \frac{x_1}{s_1}$$

and the ratio x_1/c is in general a function of y, it is convenient to write

$$F(X,Y) = F(\theta) = A_0 + A_1(1 - \cos\theta) + A_2(1 - \cos\theta)^2 + A_3(1 - \cos\theta)^3 \quad .. \quad (3)$$

where A_0, A_1, A_2 and A_3 are independent functions of Y.

On substituting this expression for $F(X,Y)$ in the integral for w from equations (1) and (2), *viz.*,

$$w = \frac{2sV}{\pi s_1}\int_0^1 F(X,Y)\,[F_0 \cot \tfrac{1}{2}\theta + F_1 \sin\theta + F_2 \sin 2\theta]\, d\left(\frac{x}{c}\right), \quad .. \quad .. \quad (4)$$

it follows that

$$\frac{s_1 w}{2sV} = \frac{1}{2\pi}\int_0^\pi [A_0 + A_1(1 - \cos\theta) + A_2(1 - \cos\theta)^2 + A_3(1 - \cos\theta)^3]$$
$$[F_0 \cot \tfrac{1}{2}\theta + F_1 \sin\theta + F_2 \sin 2\theta] \sin\theta \, d\theta$$
$$= A_0(\tfrac{1}{2}F_0 + \tfrac{1}{4}F_1) + A_1(\tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2)$$
$$+ A_2(\tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2) + A_3(\tfrac{5}{16}F_0 + \tfrac{7}{16}F_1 - \tfrac{7}{16}F_2) . \quad .. \quad .. \quad (5)$$

The continuous vorticity k will now be represented by three finite horseshoe vortices of strengths K_1, K_2 and K_3 at chordwise positions $\theta = \theta_1$, θ_2 and θ_3 respectively. Then from equation (2)

$$w = \frac{1}{4\pi s_1}\sum_i F(\theta_i) . K_i .$$

Therefore $$\frac{s_1 w}{2sV} = \sum_i F(\theta_i) . \frac{K_i}{8\pi sV}$$
$$= \sum_i k_i(A_0 + A_1\lambda_i + A_2\lambda_i^2 + A_3\lambda_i^3) , \quad .. \quad .. \quad .. \quad .. \quad .. \quad (6)$$

where $$\left.\begin{aligned} k_i &= \frac{K_i}{8\pi sV} \\ \lambda_i &= 1 - \cos\theta_i \end{aligned}\right\} i = 1, 2, 3.$$

On equating the coefficients of A_0, A_1, A_2 and A_3 in the expressions for $s_1w/2sV$ in equations (5) and (6),

$$\left.\begin{aligned}\sum_i k_i &= \tfrac{1}{2}F_0 + \tfrac{1}{4}F_1\\ \sum_i \lambda_i k_i &= \tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2\\ \sum_i \lambda_i^2 k_i &= \tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2\\ \sum_i \lambda_i^3 k_i &= \tfrac{5}{16}F_0 + \tfrac{7}{16}F_1 - \tfrac{7}{16}F_2\end{aligned}\right\} \quad \ldots \quad (7)$$

Therefore the determinant

$$\begin{vmatrix} 1 & 1 & 1 & (\tfrac{1}{2}F_0 + \tfrac{1}{4}F_1)\\ \lambda_1 & \lambda_2 & \lambda_3 & (\tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2)\\ \lambda_1^2 & \lambda_2^2 & \lambda_3^2 & (\tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2)\\ \lambda_1^3 & \lambda_2^3 & \lambda_3^3 & (\tfrac{5}{16}F_0 + \tfrac{7}{16}F_1 - \tfrac{7}{16}F_2)\end{vmatrix}$$

must vanish identically.

It will be seen that

$$8(\tfrac{5}{16}F_0 + \tfrac{7}{16}F_1 - \tfrac{7}{16}F_2) - 20(\tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2) + 12(\tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2) - (\tfrac{1}{2}F_0 + \tfrac{1}{4}F_1) \equiv 0\,.$$

λ_1, λ_2 and λ_3 are thus the roots of the cubic equation

$$8\lambda^3 - 20\lambda^2 + 12\lambda - 1 = 0\,,$$

whence

$$\left.\begin{aligned}\lambda_1 &= 0{\cdot}0990311\\ \lambda_2 &= 0{\cdot}7774791\\ \lambda_3 &= 1{\cdot}6234898\,.\end{aligned}\right\} \quad \ldots \quad (8)$$

From the first three equations in (7) it is readily shown that

$$k_1 = \frac{\lambda_2\lambda_3}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)}\,(\tfrac{1}{2}F_0 + \tfrac{1}{4}F_1) - \frac{\lambda_2 + \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)}\,(\tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2) + \frac{1}{(\lambda_1 - \lambda_2)(\lambda_1 - \lambda_3)}\,(\tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2)$$

and that k_2 and k_3 are given by cyclic expressions. On substituting the numerical values of λ_1, λ_2 and λ_3 from equations (8),

$$\left.\begin{aligned}k_1 &= 1{\cdot}2204108\mu_0 - 2{\cdot}3214231\mu_1 + 0{\cdot}9668693\mu_2\\ k_2 &= -0{\cdot}2801100\mu_0 + 3{\cdot}0010420\mu_1 - 1{\cdot}7422384\mu_2\\ k_3 &= 0{\cdot}0596992\mu_0 - 0{\cdot}6796189\mu_1 + 0{\cdot}7753691\mu_2\,,\end{aligned}\right\} \quad \ldots \quad (9)$$

where

$$\left.\begin{aligned}\mu_0 &= \tfrac{1}{2}F_0 + \tfrac{1}{4}F_1\\ \mu_1 &= \tfrac{1}{4}F_0 + \tfrac{1}{4}F_1 - \tfrac{1}{8}F_2\\ \mu_2 &= \tfrac{1}{4}F_0 + \tfrac{5}{16}F_1 - \tfrac{1}{4}F_2\,.\end{aligned}\right\}$$

Therefore

$$\left.\begin{aligned} k_1 &= 0\cdot271567F_0 + 0\cdot026893F_1 + 0\cdot048461F_2 \\ k_2 &= 0\cdot174646F_0 + 0\cdot135784F_1 + 0\cdot060429F_2 \\ k_3 &= 0\cdot053787F_0 + 0\cdot087323F_1 - 0\cdot108890F_2 \\ &\text{concentrated at respective chordwise positions} \\ x_1/c &= \tfrac{1}{2}\lambda_1 = 0\cdot049515 \\ x_2/c &= \tfrac{1}{2}\lambda_2 = 0\cdot388740 \\ x_3/c &= \tfrac{1}{2}\lambda_3 = 0\cdot811745 \end{aligned}\right\} \quad \ldots \quad (10)$$

will give a close approximation to the exact integral for w, the contribution to downwash velocity when the spanwise parameter Y is not small.

3. *Numerical Procedure.*—Falkner[2] (1949) now recommends the use of 41 spanwise vortices and 12 chordwise vortices. The long method of evaluating downwash for a particular spanwise loading involves 12 spanwise summations of 41 quantities. The 12 sums so obtained are then combined linearly using the following factors taken from R. & M. 2740[2], Table 12:

TABLE 1

x/c from L.E.	Chordwise pressure distribution		
	$\cot \frac{1}{2}\theta$	$\sin \theta$	$\sin 2\theta$
0·0417	0·1612	0·0099	+0·0182
0·1250	0·0771	0·0175	0·0262
0·2083	0·0550	0·0215	0·0250
0·2917	0·0435	0·0240	0·0201
0·3750	0·0358	0·0257	0·0128
0·4583	0·0301	0·0264	+0·0044
0·5417	0·0254	0·0264	−0·0044
0·6250	0·0215	0·0257	−0·0128
0·7083	0·0179	0·0240	−0·0201
0·7917	0·0145	0·0215	−0·0250
0·8750	0·0110	0·0175	−0·0262
0·9583	0·0070	0·0099	−0·0182

For the central 9 spanwise vortices, when $|Y| \leqslant 8$, the above table of factors is recommended. But for the remaining 32 spanwise vortices the sets of 12 chordwise factors may be replaced by those of 3 factors as determined in equations (10). The following table may then be used with excellent accuracy.

TABLE 2

x/c from L.E.	Chordwise pressure distribution		
	$\cot \frac{1}{2}\theta$	$\sin \theta$	$\sin 2\theta$
0·0495	$0\cdot2715_5$	0·0269	+0·0485
$0\cdot3887_5$	$0\cdot1746_5$	0·1358	+0·0604
$0\cdot8117_5$	0·0538	0·0873	−0·1089

4. *Accuracy of Approximation.*—In place of Table 2 previous calculations by vortex-lattice theory have used the following factors.

TABLE 3

x/c from L.E.	Chordwise pressure distribution		
	cot $\frac{1}{2}\theta$	sin θ	sin 2θ
0·25	0·5	—	+0·125
0·50	—	0·25	—
0·75	—	—	−0·125

The downwash at mid-chord has been calculated at a distance

$$\eta_1 s = 0\cdot 2s$$

from the median section of a delta wing of aspect ratio 3, shown in Fig. 1. When

$$F_0 = \sqrt{(1 - \eta^2)} \,,$$

$$F_1 = F_2 = 0 \,,$$

the procedure of section 3 gives a total downwash velocity W such that

$$\frac{s_1 W}{2sV} = \frac{1}{80}\frac{W}{V} = 0\cdot 1180 \,.$$

This corresponds to the chordwise pressure distribution cot $\frac{1}{2}\theta$ and an elliptic spanwise loading. Inaccuracies greater than $\pm\frac{1}{2}$ per cent should be avoided. Thus, when the factors k_i/F_0 from Tables 1, 2 and 3 corresponding to cot $\frac{1}{2}\theta$ are used, the contributions to the downwash given by equation (6) should be correct within $\pm$ 0·0005. The calculated values have been compared with exact evaluations of the integral for $\frac{s_1 w}{2sV}$ from equation (4) and are plotted in Fig. 1 for a for a range of

$$\eta = \eta_1 - \frac{y_1}{s} = 0\cdot 2 - Y \,.\, \frac{s}{s_1}$$

$$= 0\cdot 2 - 0\cdot 025Y \,. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

It will be seen that the factors in Table 3 are not very satisfactory, but that the values obtained by means of the new factors in Table 2 are accurate enough for $|Y| > 8$. Comparisons of the contributions using Tables 1 and 2 and the exact integration of equation (4) for smaller values of $|Y|$ are also shown in Fig. 1 on one tenth of the scale, and illustrate the discrepancies that may arise.

Similar contributions have been calculated at the same mid-chord point of the section $\eta_1 = 0\cdot 2$ of the delta wing in the particular cases $Y = \pm 8$ for the other chordwise pressure distributions sin θ and sin 2θ. The values are shown in Table 4 together with those corresponding to cot $\frac{1}{2}\theta$.

TABLE 4

Contributions to $-\frac{s_1 w}{2sV} = -\frac{1}{80}\frac{w}{V}$

η from equation (11) Chordwise pressure distribution	0 cot $\frac{1}{2}\theta$	0 sin θ	0 sin 2θ	0·4 cot $\frac{1}{2}\theta$	0·4 sin θ	0·4 sin 2θ
Exact integration : equation(4)	0·02643	0·00968	0·00538	0·02095	0·00590	0·00440
Equation (6) using Table 1 ..	0·02593	0·00930	0·00529	0·02036	0·00583	0·00443
Equation (6) using Table 2 ..	0·02694	0·00979	0·00573	0·02049	0·00579	0·00403
Equation (6) using Table 3 ..	0·0300	0·0113	0·0064	0·0225	0·0043	0·0050

It is concluded that the factors from Table 2 will satisfactorily replace those from Table 1 when $|Y| > 8$, but that a larger semi-range would be necessary if the factors from Table 3 were used.

5. *Chordwise Factors for Deflected Flaps.*—In extending the vortex-lattice theory to the problem of deflected control surfaces it is necessary to introduce chordwise pressure distributions other than those proportional to $\cot \frac{1}{2}\theta$, $\sin \theta$ and $\sin 2\theta$. The vortex strength k may then be written as

$$k = 8V\frac{s}{c}\left[G\left(\frac{\pi - \phi}{\pi}\cot \tfrac{1}{2}\theta + \frac{1}{\pi}\log_e \frac{\sin \frac{1}{2}(\theta + \phi)}{\sin \frac{1}{2}|\theta - \phi|}\right) + F_0 \cot \tfrac{1}{2}\theta + F_1 \sin \theta + \ldots\right], \quad (12)$$

where the ratio $E = \frac{\text{flap chord}}{\text{wing chord}} = \frac{1}{2}(1 + \cos \phi)$. In two-dimensional flow the first term in equation (12) corresponds to the pressure distribution when the rear part of a hinged flat plate at zero incidence is deflected through an angle $\xi = 4Gs/c$, just as the second term in equation (12) corresponds to a uniform incidence $\alpha = 4F_0 s/c$.

The downwash velocity, given by equations (2) and (12),

$$w = \frac{2sV}{\pi s_1}\int_0^1 F(\theta)\left[G\left(\frac{\pi - \phi}{\pi}\cot \tfrac{1}{2}\theta + \frac{1}{\pi}\log_e \frac{\sin \frac{1}{2}(\theta + \phi)}{\sin \frac{1}{2}|\theta - \phi|}\right) + \ldots\right]\tfrac{1}{2}\sin \theta \, d\theta$$

is treated similarly, but with reduced accuracy. It is convenient to take the vortices in the chordwise positions determined in equations (10) and to omit the term $A_3(1 - \cos \theta)^3$ in the expression $F(\theta)$ in equation (3). Thus due to the added chordwise loading

$$\frac{s_1 w}{2sVG} = \frac{1}{2\pi}\int_0^\pi \left[\left\{A_0 + A_1(1 - \cos \theta) + A_2(1 - \cos \theta)^2\right\}\right.$$

$$\left.\times \left\{\frac{\pi - \phi}{\pi}\cot \tfrac{1}{2}\theta + \frac{1}{\pi}\log_e \frac{\sin \frac{1}{2}(\theta + \phi)}{\sin \frac{1}{2}|\theta - \phi|}\right\}\right]\sin \theta \, d\theta$$

$$= A_0 \cdot \frac{\pi - \phi + \sin \phi}{2\pi} + A_1 \cdot \frac{\frac{1}{2}(\pi - \phi) + \sin \phi - \frac{1}{4}\sin 2\phi}{2\pi}$$

$$+ \frac{A_2}{2\pi}\{\tfrac{1}{2}(\pi - \phi) + \tfrac{5}{4}\sin \phi - \tfrac{1}{2}\sin 2\phi + \tfrac{1}{12}\sin 3\phi\}. \quad (13)$$

It remains to substitute

$$\left.\begin{aligned} \mu_0 &= \frac{G}{2\pi}(\pi - \phi + \sin \phi) \\ \mu_1 &= \frac{G}{2\pi}\{\tfrac{1}{2}(\pi - \phi) + \sin \phi - \tfrac{1}{4}\sin 2\phi\} \\ \mu_2 &= \frac{G}{2\pi}\{\tfrac{1}{2}(\pi - \phi) + \tfrac{5}{4}\sin \phi - \tfrac{1}{2}\sin 2\phi + \tfrac{1}{12}\sin 3\phi\} \end{aligned}\right\} \quad (14)$$

in the previous expressions for k_1, k_2 and k_3 in equation (9). Thus the contributions to the downwash from the added chordwise loading due to a deflected flap are obtained by using the factors

$$\left.\begin{aligned} k_1 &= \quad 1\cdot2204108\mu_0 - 2\cdot3214231\mu_1 + 0\cdot9668693\mu_2 \\ k_2 &= -0\cdot2801100\mu_0 + 3\cdot0010420\mu_1 - 1\cdot7422384\mu_2 \\ k_3 &= \quad 0\cdot0596992\mu_0 - 0\cdot6796189\mu_1 + 0\cdot7753691\mu_2 \end{aligned}\right\}$$

and the values of μ_0, μ_1 and μ_2 from equation (14) instead of equation (9).

These quantities have been evaluated for the range of values of $E = \frac{1}{2}(1 + \cos\phi)$ as follows:

TABLE 5

E	μ_0/G	μ_1/G	μ_2/G
0·05	0·1411572	0·1364839	0·1979956
0·10	0·1979093	0·1848983	0·2593828
0·15	0·2402512	0·2167360	0·2940243
0·20	0·2749075	0·2393129	0·3140097
0·25	0·3044990	0·2556236	0·3245398
0·30	0·3303729	0·2672940	0·3285585
0·35	0·3533308	0·2753511	0·3279835
0·40	0·3738922	0·2805097	0·3241727
0·45	0·3924150	0·2833040	0·3181425
0·50	0·4091549	0·2841549	0·3106807
0·60	0·4379866	0·2813690	0·2938442
0·70	0·4613628	0·2744418	0·2773591
0·80	0·4797404	0·2653350	0·2636373
0·90	0·4930767	0·2560876	0·2541778
1·00	0·5	0·25	0·25

TABLE 6

E	$x_1/c = 0{\cdot}0495$	$x_2/c = 0{\cdot}3887_5$	$x_3/c = 0{\cdot}8117_5$
	k_1/G	k_2/G	k_3/G
0·05	$0{\cdot}0468_5$	0·0251	0·0692
0·10	0·0631	$0{\cdot}0475_5$	$0{\cdot}0872_5$
0·15	$0{\cdot}0743_5$	0·0709	0·0950
0·20	$0{\cdot}0835_5$	0·0941	$0{\cdot}0972_5$
0·25	0·0920	0·1164	0·0961
0·30	$0{\cdot}1003_5$	0·1372	0·0928
0·35	0·1091	$0{\cdot}1559_5$	$0{\cdot}0882_5$
0·40	$0{\cdot}1185_5$	0·1723	$0{\cdot}0830_5$
0·45	$0{\cdot}1288_5$	0·1860	$0{\cdot}0775_5$
0·50	0·1401	$0{\cdot}1968_5$	0·0722
0·60	$0{\cdot}1654_5$	0·2098	$0{\cdot}0627_5$
0·70	0·1941	$0{\cdot}2111_5$	0·0561
0·80	0·2244	0·2026	0·0527
0·90	0·2530	0·1876	0·0525
1·00	$0{\cdot}2715_5$	$0{\cdot}1746_5$	0·0538

These three chordwise loading factors have been plotted against E in Fig. 2.

In carrying out the vortex-lattice theory with deflected controls it seems to be quite essential to use the fine mesh of 41 by 12 vortices to allow for the irregularities in pressure in both chordwise and spanwise directions. The tabulated chordwise factors substantially reduce the amount of computation and do not appreciably affect its accuracy.

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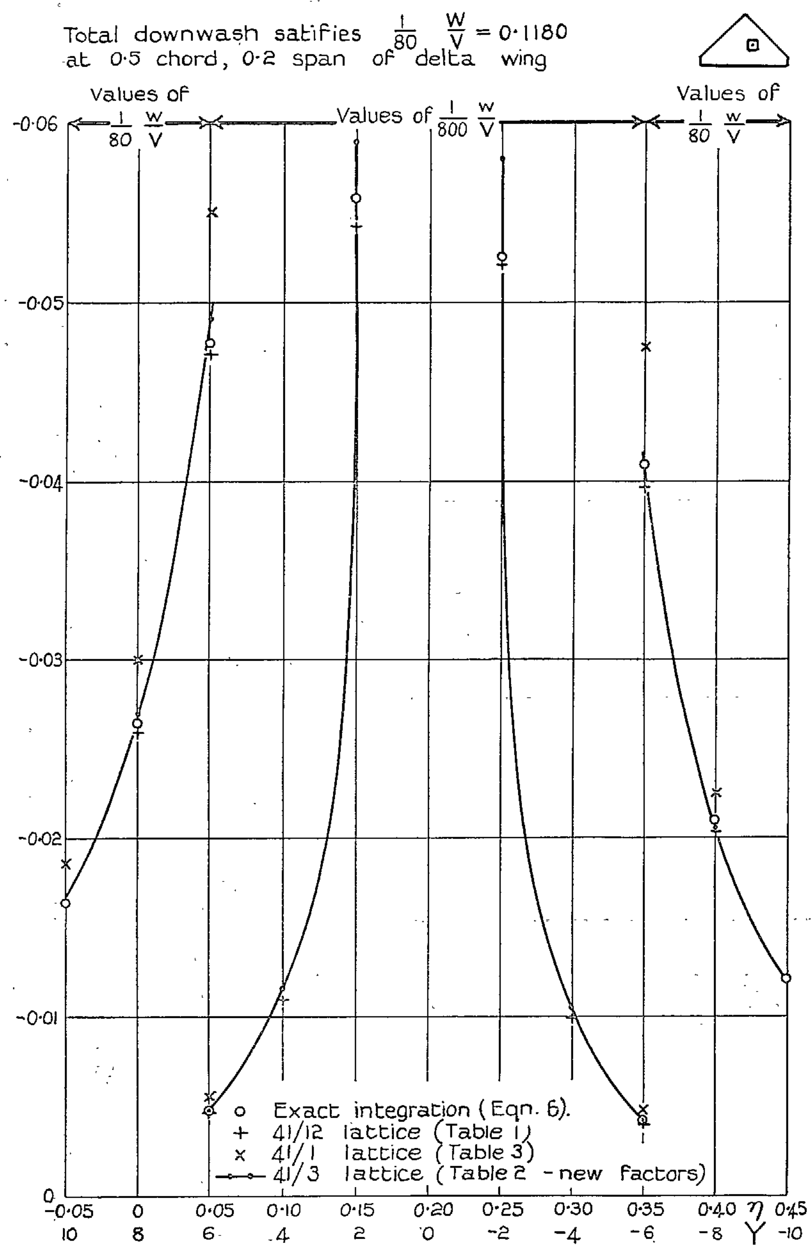

FIG. 1. Approximate and exact contributions to the downwash of a vortex lattice.

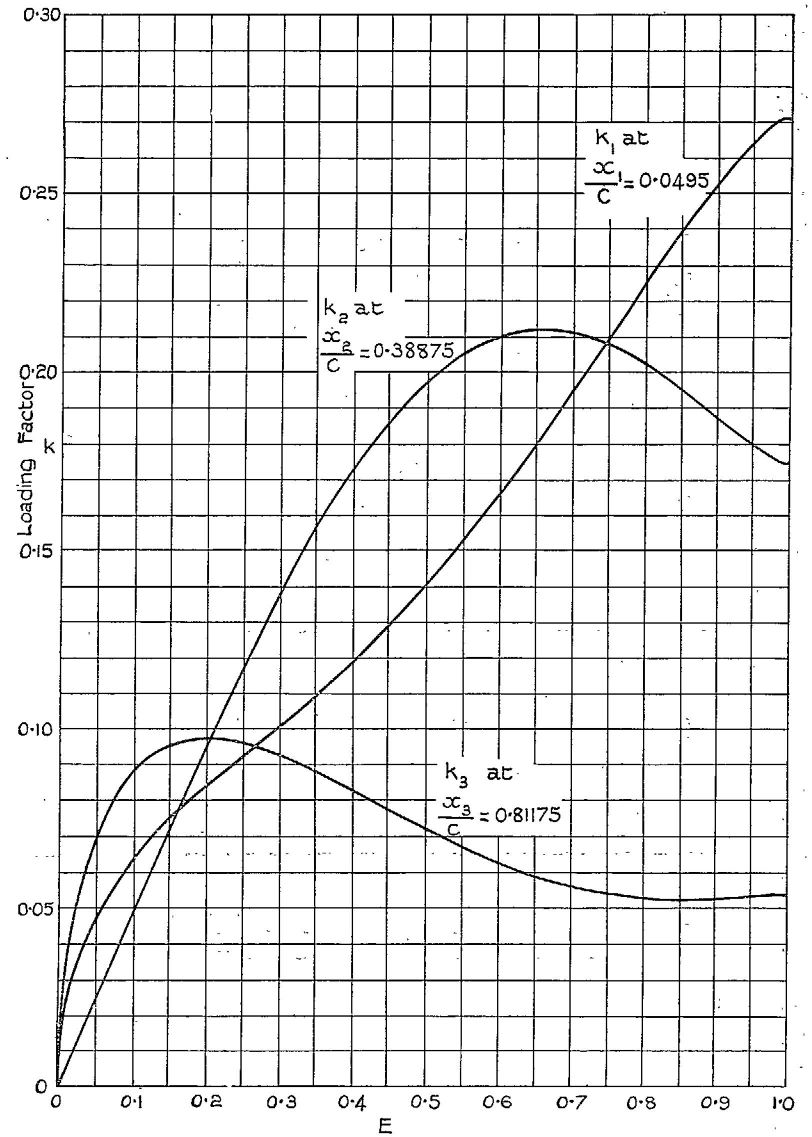

FIG. 2. Chordwise downwash factors with deflected flaps. Vortex-lattice theory | Y | > 8.

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