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Plane multiple screens in non-uniform flow, with particular application to wind tunnel settling chamber screens

P. E. HANCOCK

ABSTRACT. – The analysis of Taylor and Batchelor for a single plane screen is extended to the case of any number of arbitrarily-spaced screens of arbitrary pressure drop coefficient, K, with particular attention paid to the effect of removing non-uniformity in the mean flow. Any spacing will given an attenuation to at least 0.11 provided ΣK exceeds 2.5. Greater attenuation needs more care. The minimum spacing required for a given attenuation decrease significantly with increasing ΣK. If ΣK exceeds about 4, this minimum depends on only the number of screens and ΣK. However, measurements show that the degree of uniformity is limited by the velocity overshoot that arises in the vicinity of the wall boundary layers. © Elsevier, Paris

1. Introduction

Porous screens, usually of woven construction, are virtually always used as a means of improving mean flow uniformity and reducing free-stream turbulence in wind tunnels. Several screens are usually employed because this gives greater turbulence reduction and supposedly better uniformity. A screen has three effects on non-uniform and turbulent flow: (i) modification of the mean flow as a consequence of its pressure drop and flow deflection characteristics, (ii) modification of turbulence in the flow by the same mechanism and (iii) when at supercritical Reynolds numbers, modification of the turbulence downstream of the screen by small scale turbulence generated by the screen. Taylor and Batchelor (1949) argued that the first two can be regarded as inviscid except at the plane of the screen, so that the flow either side of a screen can be described by irrotational perturbations provided the non-uniformity or turbulence intensity is sufficiently weak. Their analysis, which was made only for a single screen, showed that the attenuation of non-uniformity is given by the well-known result, $(1 + \alpha - \alpha K)/(1 + \alpha + K)$, where K and α are the pressure drop and deflection coefficients, respectively. Davis (1957, *see* Elder, 1959) has extended the analysis for (i) to two screens.

In the context of wing tunnel settling chambers Mehta and Bradshaw (1978) suggest that screens should be spaced about 0.2 chamber heights apart in order to avoid adverse inviscid-type interference effects, and Mehta (1977) suggests the spacing should be 500 wire diameters (or roughly 100 mesh lengths). However, Hancock and Johnson (1997) have suggested from experiments that the separation can be as little as 0.02 chamber heights without any apparent adverse effects, provided the spacing is not too small in terms of mesh size. In addition, they argue from a very simple analysis that if the screens are sufficiently close together they behave as a single screen having pressure drop and deflection coefficients of ΣK and $\Pi\alpha$, whereupon the attenuation becomes $(1 + \Pi\alpha - \Pi\alpha\Sigma K)/(1 + \Pi\alpha + \Sigma K)$. As in the analysis of Taylor and Batchelor the mesh size is not a parameter, though in practice there must be a safe minimum separation in mesh lengths below which adverse effects can be expected. Such effects are likely to be akin to those that arise for a single screen when the open

School of Mechanical and Materials Engineering, University of Surrey, Guildford, Surrey, GU2 5XH, UK

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area ratio is less than about 0.57 (Bradshaw, 1965). Recently, Watmuff (1997) has shown that even very small imperfections in the weave of the settling chamber screens can have significant lasting effects in the working section flow, such as in lateral variations in an otherwise two-dimensional boundary layer. Consequently, if such irregularities decrease with solidity, rather more screens of low solidity may be better than fewer of higher solidity, preferably without increased settling chamber length.

The present contribution is concerned with the general case of any number of arbitrarily-spaced screens of arbitrary pressure drop coefficient, though for brevity results are presented only for equally-spaced screens of equal pressure drop. The distances between the screens introduce one or more additional length scales, with the result that the modes are no longer equally attenuated, and that, for example, there is no ideal ΣK giving perfect attenuation. The present results show that *any* spacing will give an attenuation (magnitude) to 0.11 or better provided ΣK is greater than about 2.5. If substantially better attenuation is required then the spacing must exceed a minimum, dependent upon the number of screens, and ΣK. Of course, in the context of wind tunnels the contraction also reduces flow non-uniformity, approximately as the inverse square of the area ratio, and a quite modest attenuation will be probably satisfactory for a large contraction ratio, though for a small contraction ratio a higher level may be desired.

Some comparisons are made with measurement for spacings set to give an attenuation (magnitude) to better than 0.03. Although agreement appears to exist in the centre of the flow, overall, the non-uniformity at this level is dominated by the boundary layer overshoot (see, for instance, Mehta 1977), which increases roughly as 0.01 ΣK. The effect of the screens on the boundary layer is beyond the scope of the present analysis, though some useful inferences can be drawn.

2. Analysis

Following Taylor and Batchelor (1949) the screen is described only in terms of a pressure-drop coefficient K and deflection coefficient, α, defined in the usual way as

$$K = \frac{\Delta p}{\frac{1}{2}\rho U^2}, \quad \alpha = v_+/v_-, \quad \text{and} \quad \alpha = w_+/w_-. \tag{2.1}$$

Δp is the pressure drop across the screen and U is the velocity perpendicular to the screen. u, v and w are the perturbation velocities in the streamwise and lateral directions, respectively x, y, z, where $U = \overline{U} + u$, $\overline{U}$ being the mean velocity ignoring the screen blockage. v_- and v_+, like w_- and w_+, denote the lateral components of velocity on the upstream and downstream faces of the screen. No other details about the screens are involved. Either side of the screen the perturbation velocity potential, ϕ, is given by $\nabla^2\phi = 0$.

Suppose the first of N screens is placed at $x = 0$, the second at $x = X_1$, and so on, and that the departure from uniformity well upstream ($x = -\infty$) is of the form

$$u_{0\,(l,m)} \sin(ly) \sin(mz). \tag{2.2}$$

The velocity on the upstream side of the screen must also be periodic in y and z with wavenumbers l and m, and so a bounded from for $\phi_{(l,m)}$ is

$$\phi_{(l,m)} = A_{0_{(l,m)}} e^{px} \sin(ly)\ \sin(mz)$$

Between any pair of screens, n and $n + 1$, the perturbation velocity potential must be of the form

$$\phi_{(l,m)} = \{A_{n(l,m)} e^{-p(X_n - x)} + B_{n(l,m)} e^{-px}\} \sin(ly)\ \sin(mz).$$

Here, X_n is the distance *between* the n^{th} and $n+1^{\text{th}}$ screen, and x is taken from the n^{th} screen. Thus, the velocity perturbations are

$$u_{(l,m)} = p\left\{(A_{n_{(l,m)}} e^{-p(X_n - x)} - B_{n_{(l,m)}} e^{-px}) + u_{n_{(l,m)}}\right\} \sin(ly)\sin(mz),$$

and

$$v_{(l,m)} = l\left\{A_{n_{(l,m)}} e^{-p(X_n - x)} + B_{n_{(l,m)}} e^{-px}\right\} \cos(ly)\sin(mz), \tag{2.3}$$

with a similar equation to the second for $w_{(l,m)}$. In the first equation $u_{n_{(l,m)}}$ is the rotational contribution. Continuity requires that $p^2 = l^2 + m^2$.

Now, the effect of a screen is to cause a change in vorticity on a streamline as it passes through the screen. By applying the z-component momentum equation once to each face of the screen, it is straightforward to show that the increase in the η-component of vorticity, $\Delta\eta$, across the screen is given by,

$$U\Delta\eta = \frac{\partial}{\partial z}\Delta p,$$

to first order. Thus, across the n^{th} screen,

$$\Delta\eta_{(l,m)} = -K_n\, q_{n_{(l,m)}}\, m \sin(ly)\cos(mz),$$

where $q_{n_{(l,m)}}$ is the perturbation velocity, $u_{(l,m)}$, *at* the screen. The vorticity component on the downstream side is therefore

$$(u_{(n-1)_{(l,m)}} - K_n q_{n_{(l,m)}})\, m \sin(ly)\cos(mz).$$

Similar equations arise for the other component of lateral vorticity; both sets imply that

$$u_{n_{(l,m)}} = u_{(n-1)_{(l,m)}} - K_n\, q_{n_{(l,m)}}. \tag{2.4}$$

The deflection by the n^{th} screen implies that

$$A_{n_{(l,m)}}\, e^{-pX_n} + B_{n_{(l,m)}} = \alpha_n\left\{A_{(n-1)_{(l,m)}} + B_{(n-1)_{(l,m)}}\, e^{-pX_{n-1}}\right\} \tag{2.5}$$

Finally, continuity requires that

$$q_{n_{(l,m)}} = p\,(A_{n_{(l,m)}}\, e^{-pX_n} - B_{n_{(l,m)}}) + u_{n_{(l,m)}} \tag{2.6}$$

and that

$$q_{(n+1)_{(l,m)}} = p\left\{A_{n_{(l,m)}} - B_{n_{(l,m)}}\, e^{-pX_n}\right\} + u_{n_{(l,m)}} \tag{2.7}$$

Equations 2.4 to 2.7 describe the whole flow, and are straightforwardly solved numerically by first writing them (omitting the suffices l, m) as

$$\begin{aligned}
q_{n+1} &= \{pA_n - pB_n\, e^{-pX_n}\} + u_n \\
u_{n+1} &= u_n - K_{n+1}\, q_{n+1} \\
pA_{n+1}\, e^{-pX_{n+1}} + pB_{n+1} &= \alpha_{n+1}\{pA_n + pB_n\, e^{-pX_n}\} \\
pA_{n+1}\, e^{-pX_{n+1}} - pB_{n+1} &= q_{n+1} - u_{n+1}
\end{aligned}$$

where $B_0 = 0$ and $A_N = 0$. Since these equations are linear in pA_n and pB_n, A_0 can be found from two initial guesses and interpolation to give $A_N = 0$. The upstream amplitude, u_0, is arbitrarily taken as unity. Some additional details are given by Hancock (1997).

3. Analytical results

Attention is confined here to the attenuation provided for equally spaced screens of equal pressure drop, with a view to the conditions for optimum attenuation. The deflection coefficient, α, has been calculated from $\alpha = (1-K/8)/(1+K/8)$ for $K \leq 1.5$ and from $\alpha = 1.1/(1+K)^{0.5}$ for $K > 1.5$ (Dryden and Schubauer, 1949).

Figure 1 shows the modal attenuation of N screens, $\{u_N\}_{(l,m)}/\{u_0\}_{(l,m)}$, as a function of spacing pX and pressure drop ΣK, for K of 0.5, 1, 1.5 and 2, where the numbers adjacent to the various curves denote ΣK. The variation with pX is greatest where pX is small, and the variation is fairly weak beyond pX of about 2. pX is of course the distance between adjacent screens normalised with the length scale $1/p$, and for X larger than about $4/p$ the screens behave (for this wave number) as if they were infinitely distant.

The four sets of curves in Figure 1 are comparable in shape, in two respects. Firstly, all the curves have a common feature of a single minimum, and for ΣK larger than about 4 the curves are predominantly negative, but within -0.11. Secondly, inspection shows that the variation with pX is such that the curves of a given ΣK are fairly comparable one to another when plotted against pXN. That is, for example, two screens each of $K = 2$, separated one unit apart, will have about the same effect as four screens each of $K = 1$, each separated by half a unit. This is discussed further later.

For any given upstream velocity profile the wave number p will cover a range upwards from a minimum corresponding to the longest wavenumbers, (*i.e.* lowest l, m) in the upstream flow. The range of pX, which is of course proportional both to wavenumber and spacing, may be denoted $(pX)_1$, $(pX)_2$, ..., $(pX)_i$, ... corresponding to the modes of the upstream flow, (l, m), of amplitude $u_{0(l,m)}$, where $(pX)_{i+1} > (pX_i)$. These curves show that except in the very special circumstance of a single mode there is no condition for perfect attenuation, unlike the case for a single screen, or in the limit of zero separation. In many instances, such as in wind tunnel settling chambers, the modal amplitudes are likely to broadly decrease with increasing wave number, the non-uniformity being predominantly large scale. Provided ΣK is greater than about 2.5 the magnitude $\{u_N\}_{(l,m)}/\{u_0\}_{(l,m)}$ is less than 0.11 for *any* screen spacing. Whether or not an attenuation to better than 0.11 is sufficient will depend upon the magnitude of the non-uniformity in the flow and the degree of attenuation required. It is likely that in the case of wind tunnels this will be adequate provided the contraction ratio is reasonably large, but for a small ratio or some special purpose better performance may be sought.

Figure 2 summarises Figure 1 in terms of upper and lower bounds, as functions of ΣK. The lower bound is formed from the minimum in the attenuation curves, and it is striking that the individual points (which strictly should not be joined by lines) fall close to a single curve, almost independent of the number of screens. The upper bound is formed partly by the case of infinite separation, where the discrete points also fall close to a single curve, and partly by the case of zero separation, as given by Hancock and Johnson (1997). Contrary to what might be supposed, the attenuation provided by finite spacing does not fall within a band defined by infinite and zero spacing. A ΣK of about 3.2, which is close to that recommanced by Mehta, implies an attenuation within about ± 0.04, while a ΣK of about 6 corresponds to the minimum in the lower bound, the attenuation improving only slowly with increasing ΣK.

If an attenuation much better than 0.1 is required the screens need to be placed more carefully. For example, from Figure 1c, two screens each of $K = 1.5$ will give an attenuation within ± 0.02 for any spacing (unless the mode amplitudes for $(pX)_i$ higher than about 2 should happen to be large). However, if a third screen of the same K is added the attenuation will be degraded to as much as –0.08. To recover an attenuation of –0.02 the spacing must be such that $(pX)_1$ is about 1.5, or larger. Note, assuming that the higher mode amplitudes are not zero, only the larger of the two pX is regarded as appropriate as a safe measure of separation. In terms of a settling chamber (see next section) this is a spacing of $1.5/2\pi$, *i.e.* 0.24 chamber heights, and concurs with the empirically based recommendation of Mehta and Bradshaw.

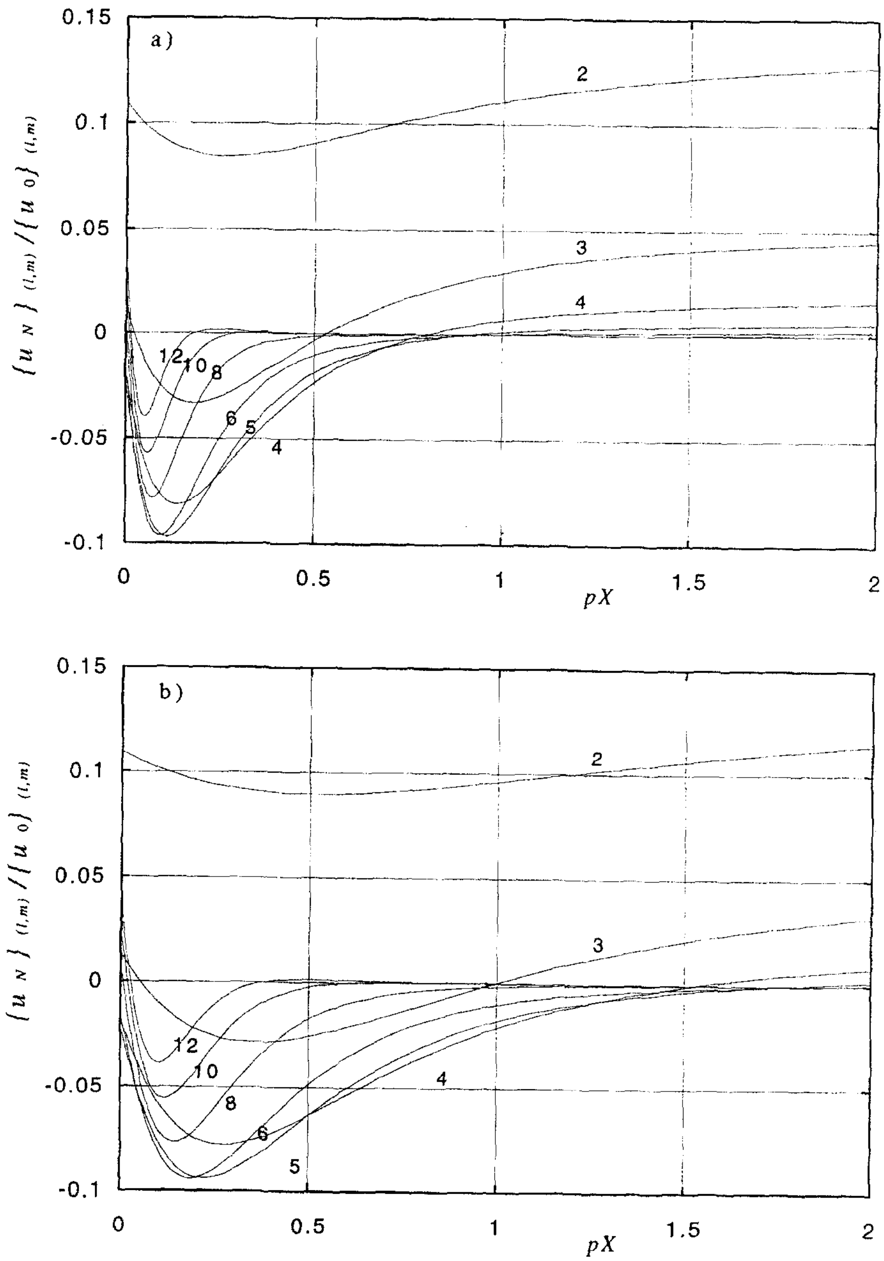


Fig. 1. – Modal amplitude $\{u_N\}_{(l,m)}/\{u_0\}_{(l,m)}$ as a function of pX and ΣK. a) $K = 0.5$; b) $K = 1.0$.

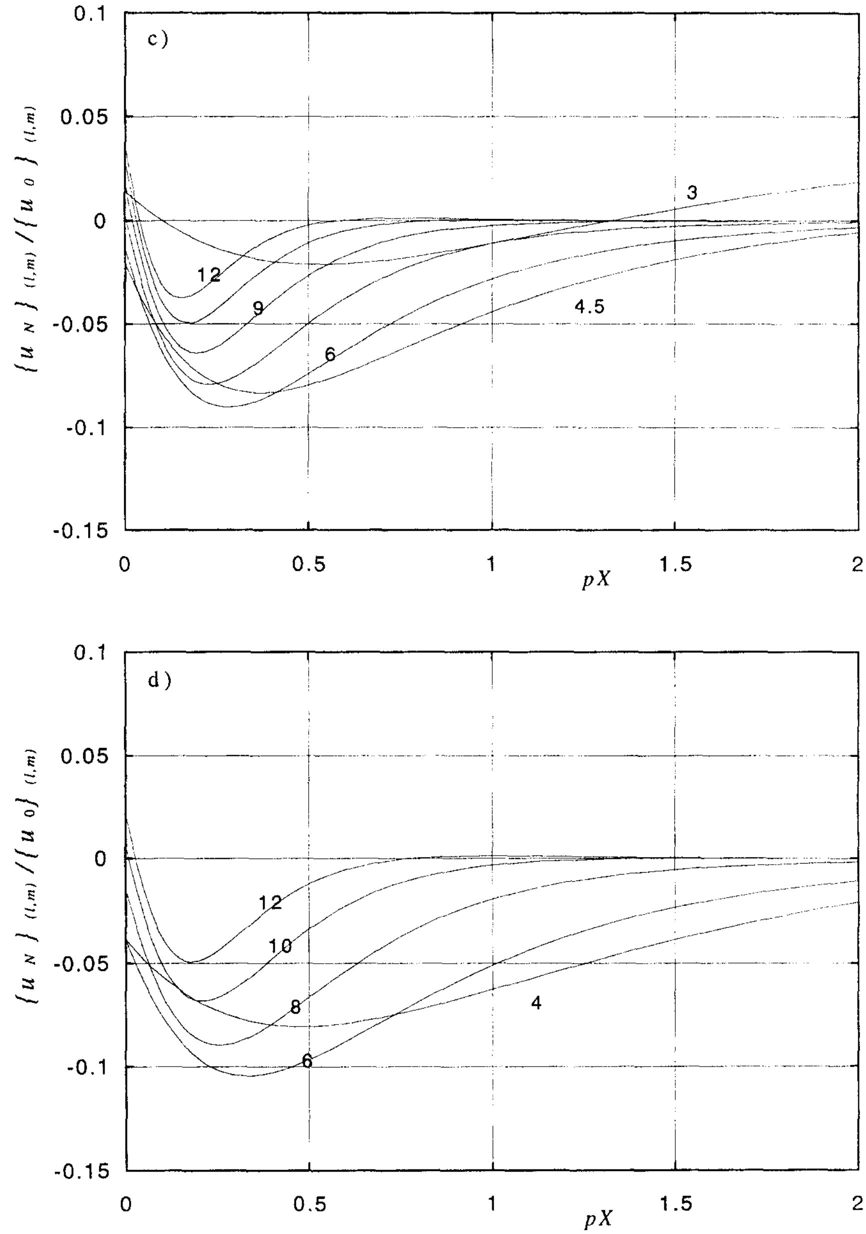


Fig. 1. – Modal amplitude $\{u_N\}_{(l,m)}/\{u_0\}_{(l,m)}$ as a function of pX and ΣK.
c) $K = 1.5$; d) $K = 2.0$.

Interestingly, the curves of Figure 1 imply that significantly smaller spacings can be employed as the number of screens increases and the total pressure drop, ΣK, increases. By way of example, Figure 3 shows the minimum separation, expressed in terms of $(pX)_1/2\pi$, required to give attenuation to (–)0.03 when ΣK is 4 or greater. Again, $(pX)_1$ is the larger of the two values at –0.03. For example, four screens, each of $K = 1.5$, require $(pX)_1/2\pi$ to be not less than 0.15. Six screens of $K = 1$ require $(pX)_1/2\pi$ to be not less than 0.11. Twelve screens of $K = 0.5$, require $(pX)_1/2\pi$ to be not less than 0.05. Similar sets of curves exist for other attenuation levels. For instance, an attenuation to better than (–)0.01, requires the intervals to be about 50% larger.

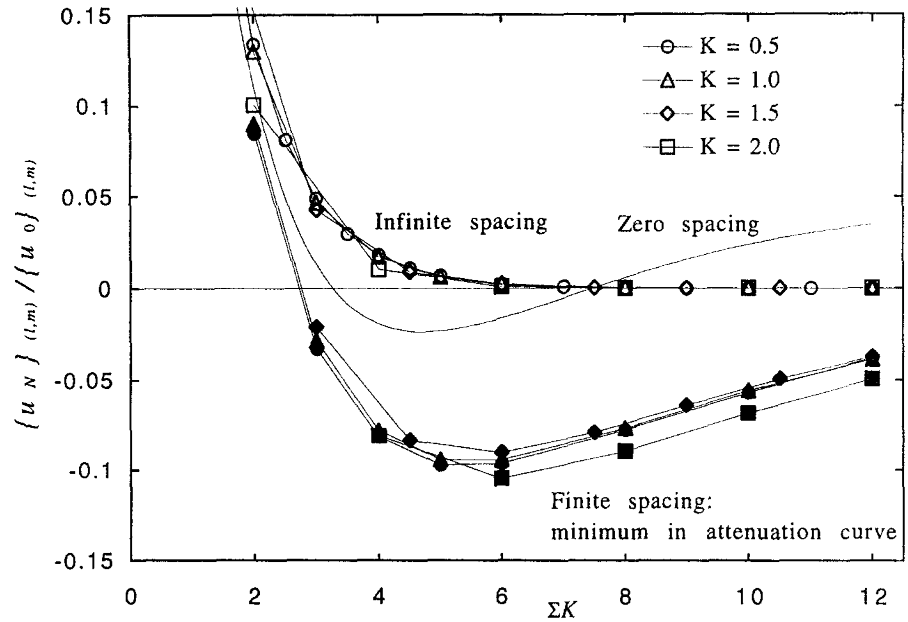


Fig. 2. – Attenuation bounds as a function of ΣK.

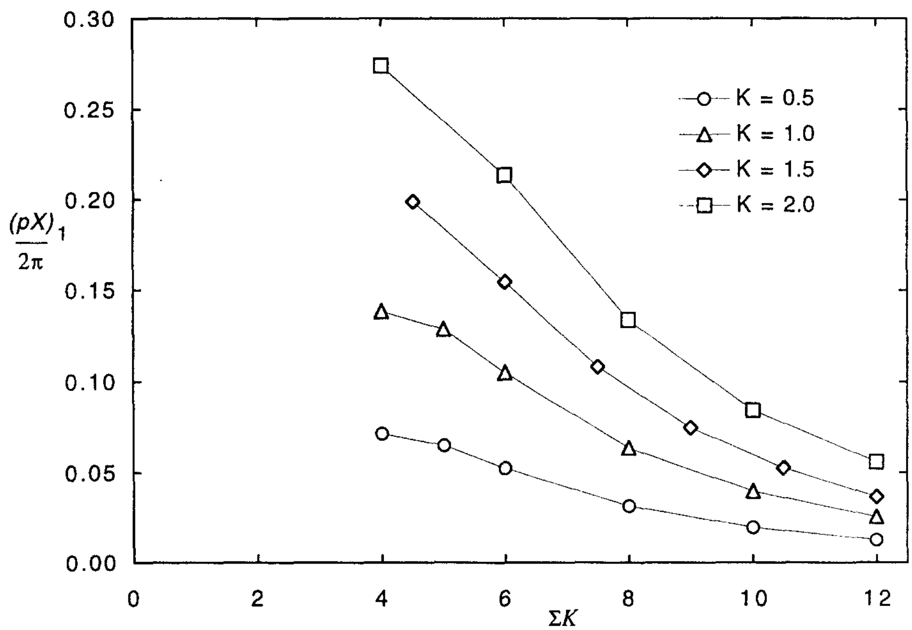


Fig. 3. – Minimum spacing to give an attenuation $\{u_N\}_{(l,m)}/\{u_0\}_{(l,m)}$ to (–)0.03, as a function of ΣK (>4) and N.

The curves of the type shown in Figure 3 exhibit a particularly interesting feature if they are recast in terms of $N\,(pX)_1/2p$ and ΣK, principally, that they fall close to a single curve for a given level of attenuation, as shown in Figure 4. This appears to be a fortuitous though highly convenient result. A crude explanation appears to be that, say, doubling the number of screens but halving the K of each reduces the quantitative effect each screen has to half the previous effect, a given quantitative effect extending half the distance. In support of this argument

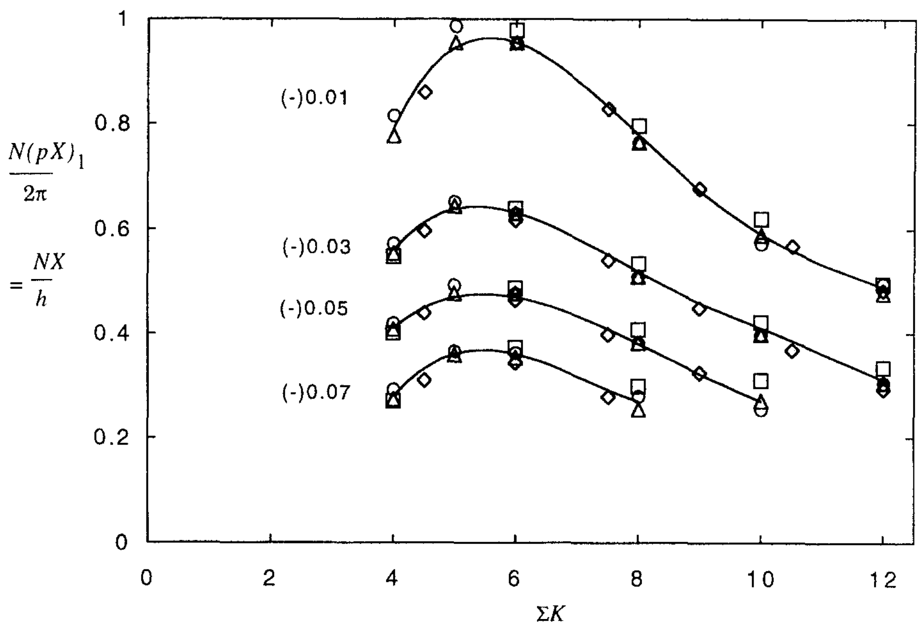


Fig. 4. – Spacing parameter NX/h as a function of ΣK. Attenuation to better than 0.07, 0.05, 0.03 and 0.01. Symbols as in Figure 3.

it is significant that the variation of attenuation with K for a single screen is roughly linear for K less than about 1. The curves of Figure 4 are also approximately self similar, scaling as $(0.75+28.5 \times \text{attenuation limit})^{-1}$.

Qualitatively, though not quantitatively, the general implications drawn here also apply to the duct wall boundary layers, even though the non-uniformity is no longer weak. Very near the wall the assumptions of the analysis are met in that the streamlines cannot be significantly displaced or at a significant angle. It is only further out, where the velocity deficit is less where the displacement and angle can be significant. This point has been noted by Mehta, and he shows that is is the decreased pressure drop coefficient that causes the observed overshoot (for a single screen). Over and above this mechanism, multiple screens will contribute to an overshoot if the mode amplitudes are negative. This is discussed further in the next section.

4. Comparisons with measurements

Measurements were made in a 305 mm square working section, 1.8 m in length, with the screens placed at the mid position, as described by Hancock and Johnson. The same flow generator was used to produce a two-dimensionally non-uniform flow. As before, the flow generator was far enough upstream of the screens for the flow from the generator to have effectively reached its asymptotic shape. The same screens of woven polyester were employed, each having a mesh size of 1.5 mm and thread size of 0.35 mm, mounted on aluminium frames. Separation between screens was provided by wooden spacer frames. Measurements where made using a digitally linerised single hot-wire anemometer. The comparative accuracy of the mean velocity measurements is better than ±0.5%. The vertical velocity, v, implied by the analysis is negligible compared with U, so the hot-wire measurements were of the longitudinal velocity, $\overline{U} + u$, alone (though the measurements here were confined to the far-field were v is in any case zero). The pressure drop coefficient, K, per screen was taken as 1.24 to within ±0.02, independent of the number of screens. Further details are given by Hancock and Johnson.

For a bounded flow l in equation 2.2 is replaced by $2\pi i/h$, where $i = 1, 2, 3$, ... now represents the i^{th} mode, and h is the height of the flow. Therefore, pX becomes $2\pi iX/h$. In these tests three and five screens were

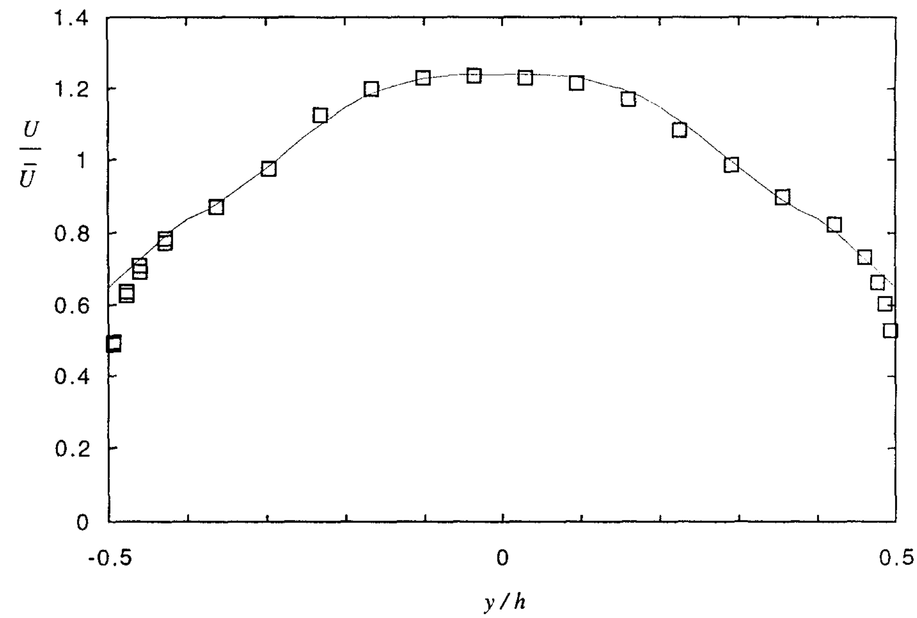


Fig. 5. – Upstream velocity profile generated by flow generator. Line is supposed profile ignoring boundary layers.

spaced according to Figure 4, for an attenuation to –0.03. From Figure 4 (or, alternatively, interpolating from Figure 3) three screens having $\Sigma K = 3.72$ require NX/h to be about 0.54 – *i.e.* intervals, X/h, of 0.18. Five screens having $\Sigma K = 6.2$ require NX/h to be about 0.61 – *i.e.* intervals, X/h, of 0.12. The overall lengths between the first and last screens, $(N-1)X/h$, are then 0.36 and 0.48, respectively. Seven screens, say, would have required an interval of 0.07 and a distance between first and lost of 0.41. In the tests the three screens were placed at intervals, X/h, of 0.17 and the five screens at intervals of 0.12.

Figure 5 shows the inlet profile. The slight asymmetry in the flow was because the flow generator was not quite symmetric, but this is ignored here, its effect being only slight in the measurements downstream of the screens. For a symmetric profile the i^{th} mode is given by $(u_0)_i \cos(2\pi i y/h)$, where y is measured from the centre. Figure 5 also shows the supposed form of the inlet profile, disregarding the boundary layers, from which $(u_0)_i$ have been calculated. These are given in Table I for the first ten terms. The results presented here have been evaluated from the first twenty terms of Fourier series defined by forty equal intervals in y/h.

TABLE I. – Fourier amplitudes for the inlet profile.

i	$(u_0)_i/\overline{U}$		
1	0.259608	6	–0.009125
2	–0.048295	7	0.005906
3	0.006572	8	–0.005177
4	–0.015267	9	0.002528
5	0.013157	10	–0.001500

Figure 6 shows the predicted residual far-field non-uniformity for a range of intevals between three and five screens. The intervals are given in terms of $2\pi X/h$, the present tests corresponding to 1.07 and 0.75, for the three- and five-screens cases, respectively. The cases considered by Hancock and Johnson correspond to $2\pi X/h$ of 0.126, and from Figure 6 it can be seen that the predicted residual non-uniformity, while not the largest, is

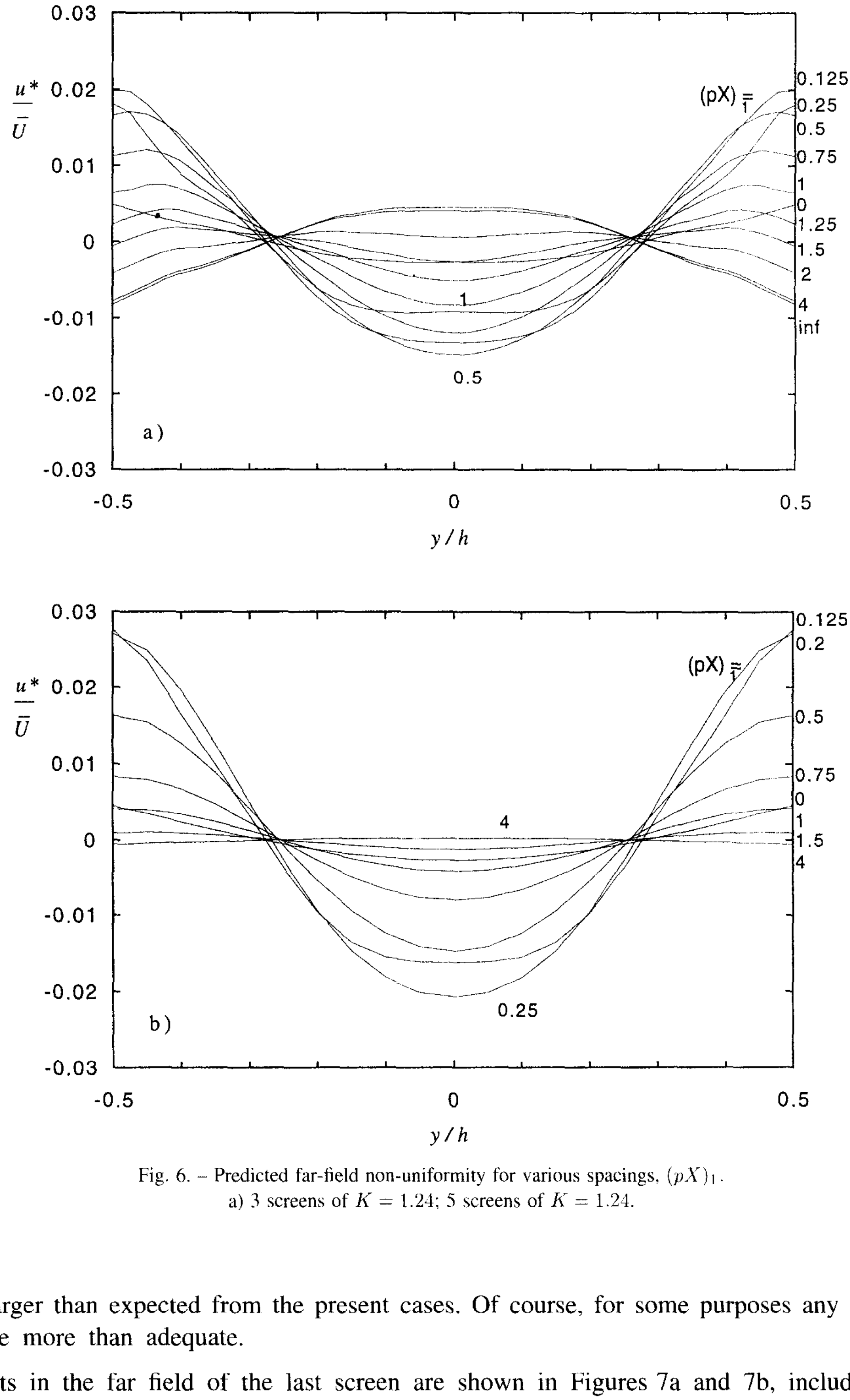
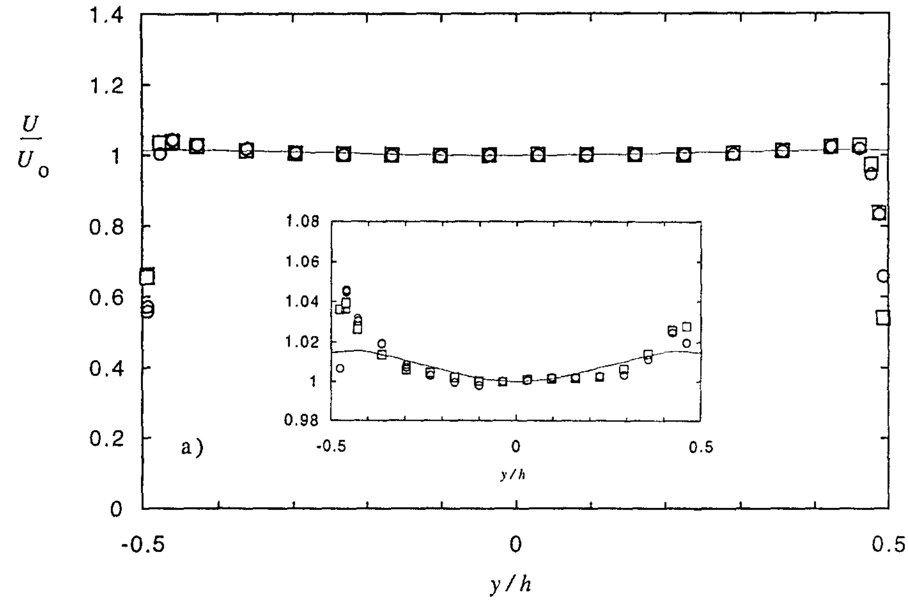


Fig. 6. – Predicted far-field non-uniformity for various spacings, $(pX)_1$.
a) 3 screens of $K = 1.24$; 5 screens of $K = 1.24$.

substantially larger than expected from the present cases. Of course, for some purposes any of the predicted profiles will be more than adequate.

Measurements in the far field of the last screen are shown in Figures 7a and 7b, including the profiles measured with a uniform upstream flow, and predicted profiles. These profiles are normalised by the velocity in the centre of the flow, U_0, and the inset figure shows the same data against a finer scale for velocity. The flow is broadly the same, irrespective of the presence or absence of upstream non-uniformity. The overshoot



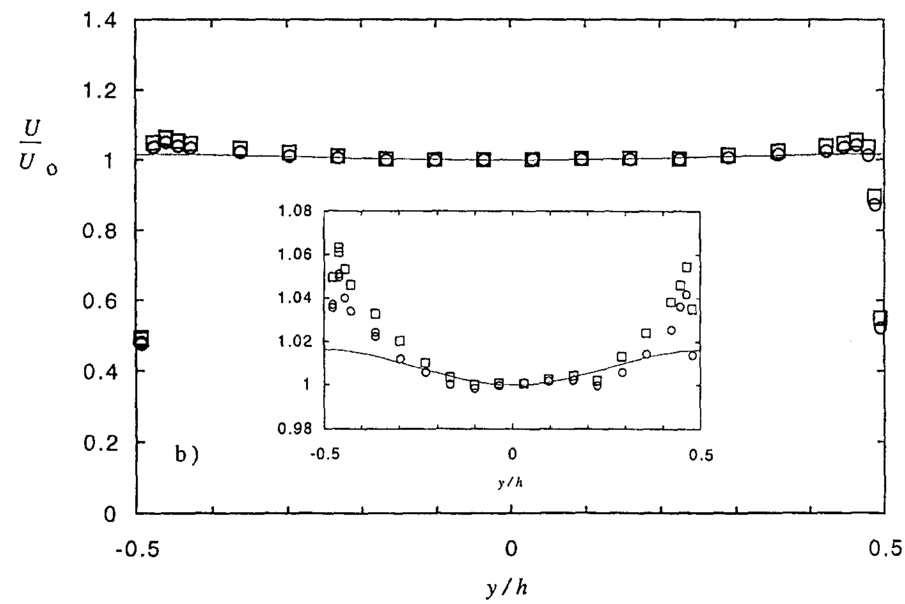


Fig. 7. – Measured far-field velocity profiles.
a) 3 screens spaced 0.17 h. b) 5 screens spaced 0.12 h. Insets show data on a finer scale.

can be clearly seen, the spatial extent of which is much larger than the thickness of the upstream boundary layer, which was typically 0.05h deep.

At this point it is useful to examing the implications of the analysis for the boundary layer ignoring for the moment the violations. As an example, Figure 8 shows the predicted far-field perturbation for a boundary layer of depth, 0.06h, beneath a uniform flow, for a range of screen spacings. Now although the size of the departure from uniformity shown in Figure 8 is less than observed in Figure 7, two key points are illustrated. Firstly, the spatial extent is much larger than the thickness of the boundary layer (other than when the spacing is small or large), and comparable with that observed in Figure 7. This arises because the uniform part of the flow requires the low wave number amplitudes to be of alternating sign, and because the amplitudes are not equally attenuated, except for zero and wide spacing. For a single screen there are only two length scales – the boundary layer thickness and the duct height – whereas for multiple screens there are also the screen spacings. Also, the extent from the wall does not scale simply on the bondary layer thickness by some fixed factor. Secondly, even though the assumptions of the analysis are not adhered to in the vicinity of the boundary layer, it seems very unlikely than an exact analysis would not show the effect of the boundary layer to extend well beyond the boundary layer edge. In summary, in addition to the non-linear, incidence-dependent overshoot mechanism discussed by Mehta, there is also, though reltively weak, a linear, spacing dependent mechanism.

Strictly, it is not legitimate to subtract one profile from the other in Figure 7, because, as just discussed, the overshoot arises largely from of the change of the screen properties with incidence angle at the screen. Although the screen causes significant deflection of the streamlines in the boundary layer vicinity, the streamline positions would be, to a first approximation, the same whether or not the upstream flow was uniform; it is only the change of screen properties with incidence that means subtraction is not formally valid. Were superposition legitimate we would expect the profiles with the generator present to be slightly less uniform than when it is absent. However, while the five screens case was slightly less uniform, the three-screens case shows negligible difference. This suggests the interaction between screens and the boundary layer may be complicated, though it is probably still valid to suppose that viscous effects can be assumed to be confined to the plane of the screen.

The fact that the predicted residual uniformities were deliberately really quite small, and the fact that there is little difference between the respective pairs in Figure 7, though not strictly validating the analysis, means that the analysis is at least approximately substantiated, and makes it hard to believe that the analysis would not be substantiated further were it possible to eliminate the contribution from the boundary layer. Of course, there is some degree of upstream non-uniformity above which the assumptions in the analysis must become appreciably inaccurate. The present results suggest that a magnitude of ± 0.3 is at least not appreciably beyond this limit.

Defining the overshoot as a whole by the fractional difference between maximum and minimum velocity, $\Delta U/U$, the overshoot increases roughly as $0.01\ \Sigma K$. This is more than suggested by Hancock and Johnson.

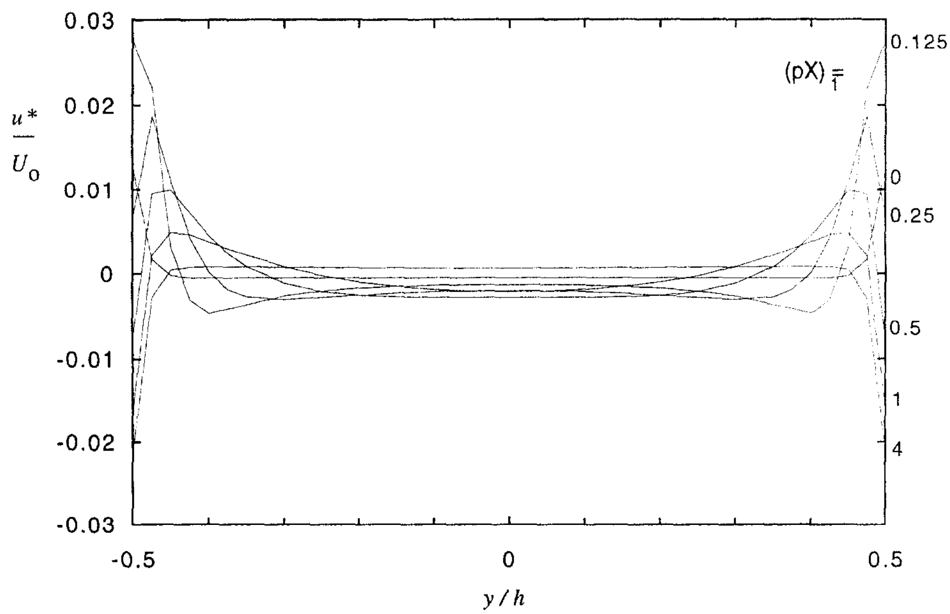


Fig. 8. – Predicted effect of 3 screens on typical upstream boundary layer as a function of spacing.

In the two cases of Figure 7, the worst predicted uniformity (*Fig.* 6) is still only about half the respective overshoot. The overshoot will inevitably limit the degree of uniformity that can be achieved. Supposing that the size of the overshoot is always as found here, then a ΣK of about 3 is likely to be a reasonable compromise between suppressing and generating non-uniformity, concurring with Mehta and Bradshaw. At this ΣK Figure 1 implies the spacing (in terms of h) is unlikely to be critical.

5. Concluding remarks

The extension of the analysis of Taylor and Batchelor to the case of multiple screens of arbitrary pressure drop and spacing is essentially straightforward. The present considerations have been confined to equaly-spaced screens of equal pressure drop coefficient, primarily in the context of wind-tunnel settling chamber screens. It seems likely that similar conclusions to those drawn here would follow for unequal spacing and unequal pressure drop.

The attenuation achieved generally depends upon modal amplitudes of the upstream flow. Any spacing will always give an attenuation to at least 0.11 provided ΣK is greater than 2.5. (The spacing must be sufficiently large in terms of mesh size.) Greater attenuation requires more care, in general requiring specific calculation. However, if the lowest mode is attenuated the least, as will quite often arise, then some further general guidelines follow. Firstly, and unexpectedly, the intervals required decrease significantly as ΣK increases. Secondly, and also surprising, the spacing required to give attenuation to levels significantly below 0.1 can be expressed in terms of approximately single curves, dependent on only ΣK and the number of screens (*Fig.* 4).

The degree to which the non-uniformity can be eliminated across the whole flow is constrained by the velocity excess or overshoot arising from the boundary layer flow through the screens. The overshoot is caused by the flow-angle dependence of screen properties as discussed by Mehta, and, relatively, weakly, by the effect of screen spacing. The measurements here indicate that the overshoot increases roughly as 0.01 ΣK, implying a likely reasonable balance between suppressing and generating non-uniformity when ΣK is about 3, where the spacing is not particularly important (providing it is sufficient in terms of mesh size). Of course, a larger overshoot may not matter if it is eliminated by the growth of the boundary layer.

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