



A guide to the alleviation of the base drag of a flat plate with a blunt trailing edge



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A GUIDE TO THE ALLEVIATION OF THE BASE DRAG OF A FLAT PLATE WITH A BLUNT TRAILING EDGE

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1. NOTATION AND UNITS

Any dimensions quoted are in the units given in the original work, whether or not they conform to those given by ESDU in terms of SI or British units. Where they differ from these two sets, lengths are typically given in inches (1 in. = 25.4 mm or 0.0254 m) or millimetres. If required, a useful approximate conversion is 1 m $\approx$ 39.37 in. or 3.281 ft. Conversions for these and other units are given in ESDU CFA.

		SI	British
C_{Db}	base drag coefficient, referred to base thickness t for two-dimensional flow and base area wt for three-dimensional flow, and kinetic pressure, q_1		
$(C_{Db})_{baseline}$	value of C_{Db} for baseline case, <i>i.e.</i> straight, unswept, blunt trailing edge		
$(C_{Db})_{\Lambda}$	value of C_{Db} for sawtoothed trailing edge, see Equation (6.3)		
$(C_{Db})_{\Lambda=0}$	value of $(C_{Db})_{\Lambda}$ for $\Lambda = 0$		
ΔC_{Db}	reduction in $(C_{Db})_{baseline}$ due to trailing-edge device, Equation (4.1)		
C_{pb}	base pressure coefficient, $(p_b - p_1)/q_1$		
$(C_{pb})_{av}$	spanwise average of C_{pb}		
d	cylinder diameter	m	ft
f_v	vortex shedding frequency	Hz	Hz
f_{v1}, f_{v2}	characteristic values of f_v , see Section 6.2.1	Hz	Hz
h_{cav}	depth of trailing-edge cavity, see Sketches 5.1 and 5.2	m	ft
h_{step}	depth of rearward facing step, see Section 4.1	m	ft
l	plate length, see Sketch 4.1	m	ft
l_a	length of parallel aft section of plate, see Sketch 4.1	m	ft
l_f	length of plate forward section, see Sketch 4.1	m	ft
l_{lip}	length of cavity extended lip, see Sketches 5.1(b) and 5.1(c)	m	ft
l_{ra}	length from base to reattachment point on splitter plate for separated shear layer, see Section 4.2	m	ft
l_{saw}	wave height of sawtooth, see Sketches 6.1(b) and 6.1(e)	m	ft
l_{seg}	length of segment, see Sketches 5.2 and 6.1(c) to 6.1(e)	m	ft

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l_{sin}	wave height of sine wave, see Sketch 6.1(a)	m	ft
l_{sp}	length of splitter plate, see Sketches 4.1 and 6.1(d)	m	ft
l_{step}	length of rearward facing step, see Section 4.1	m	ft
M_1	free-stream Mach number		
p_b	base pressure	N/m ²	lbf/ft ²
p_1	free-stream static pressure	N/m ²	lbf/ft ²
q_1	free-stream kinetic pressure	N/m ²	lbf/ft ²
R_d	Reynolds number based on d and free-stream properties		
R_l	Reynolds number based on l and free-stream properties		
R_t	Reynolds number based on t and free-stream properties		
St	Strouhal number for vortex shedding at base, $f_v t / U_1$, see Section 4.3		
t	base thickness, see Sketches 4.1 and 5.1	m	ft
U_1	free-stream velocity	m/s	ft/s
w	base width (for three-dimensional flow), see Sketches 4.4 and 4.5	m	ft
w_{gap}	width of gap between segments, see Sketches 5.2 and 6.1(c) to 6.1(e)	m	ft
w_{saw}	wavelength of sawtooth, see Sketches 6.1(b) and 6.1(e)	m	ft
$(w_{saw})_{120}$	value of w_{saw} for $\theta_{saw} = 120^\circ$, with $l_{saw} = 2t$, see Sketch 6.6	m	ft
w_{seg}	width of segment, see Sketches 5.2 and 6.1(c) to 6.1(e)	m	ft
w_{sin}	wavelength of sine wave, see Sketch 6.1(a)	m	ft
y	spanwise (lateral) coordinate with origin as shown in Sketch 6.1	m	ft
θ_{saw}	apex angle of sawtooth, see Sketches 6.1(b) and 6.1(e)	deg	deg
Λ	“sweepback” angle of sawtooth ($90^\circ - \theta_{saw}/2$), see Sketch 6.1(b)	deg	deg

2. INTRODUCTION

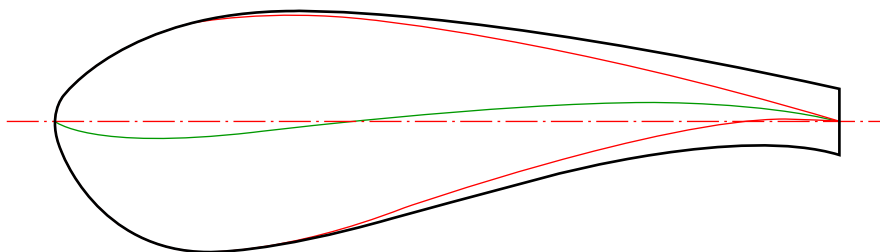
The subsonic flow of the turbulent boundary layers over the upper and lower surfaces of a flat plate with a blunt trailing edge separate at the base to form an unsteady, periodic wake in the form of a vortex street. The oscillating wake induces a substantial base drag, much higher than that for a non-periodic wake in the same situation. Appendix B of ESDU 10016 (Reference 35) provides a simple empirical method for the prediction of the base drag due to a blunt flat plate (at zero angle of attack) in two-dimensional subsonic flow, together with an approximate guide to the effects of three-dimensional flow.

For aircraft, and in many other applications, it is important to maintain low drag and so various means have been tested whereby the wake periodicity is controlled – either eliminated or moderated. The object of this Data Item is to describe the devices used and to provide guidance on their effectiveness in reducing base drag at subsonic and low supersonic speeds. The four classes of trailing-edge device that have been tested, *i.e.* base bleed, splitter plates, cavities, and non-linear trailing edges are discussed in Sections 3 to 6, respectively, with particular reference to the base drag alleviation and any other useful aerodynamic aspects of each device. Concluding remarks are given in Section 7, which also includes a table summarising the possible subsonic base drag reductions for the various devices. By way of introduction, Section 2.1 gives a brief historical background to base drag due to trailing-edge blunting.

2.1 Background to Base Drag due to Trailing-edge Blunting

The use of blunt-based aerofoils has long been considered in the aircraft industry, with research concerning the effects of blunting on lift and drag dating back to the mid-1920s (Reference 24). The associated problem of base drag alleviation dates back to at least the mid-1950s (References 15 and 17), with a more widely-based effort being made in the 1960s (Derivations 3, 4, 5, 8 and 9). The early work on the blunting of aerofoil trailing edges referred to by Hoerner (Reference 24) showed that the lift-to-drag ratio could be increased by thickening the trailing edge of thick sections. To illustrate that he provides data from some German wind-tunnel tests in 1943 showing the considerable gains in lift-to-drag ratio for a 0.4 thickness-to-chord ratio symmetrical section by the addition of increasing thickness aft of the maximum, giving a trailing-edge thickness of $0.4 \times$ maximum thickness. Of course, as Hoerner points out, the unmodified section suffered boundary-layer separation upstream of the sharp trailing edge, and the modified section, with its shallower aft surface slope, delayed separation up to the blunt trailing edge. Although the base drag due to the blunting resulted in a larger drag at low lift, the shallower aft slope allowed a much higher lift to be attained before the stall, with a lower lift-dependent drag increase – hence a larger lift-to-drag ratio.

The rapid growth in recent years in wind power generation has exposed a problem previously experienced with the lift characteristics of the thick inboard sections of aircraft propellers. In order to improve the performance of the similarly thick inboard sections used in the rotor blades of large wind turbines, the use of a thickened trailing edge has been proposed, see References 27 and 30, for example. For a cambered section, particularly one with large aft camber, the preferred method of blunting is to add thickness symmetrically about the aft camber line, thus adding trailing-edge thickness while maintaining the original camber distribution, as shown in Sketch 2.1.



Sketch 2.1 Addition of aft thickness for a cambered aerofoil

Notwithstanding the addition of base drag, significant gains in lift-to-drag ratio have been demonstrated in low-speed wind-tunnel tests on thick aerofoils with both free and fixed boundary-layer transition (References 27 and 30). Thickened trailing edges have an additional benefit in terms of ease of construction, rigidity *etc.* As in the aircraft application, the addition of base drag is similarly a problem in the power generation application, with the further problem of noise generated by the periodic base flow. Various solutions to these problems have been suggested (References 33 and 34), based largely on previous aircraft research using flat plates, as discussed in Sections 3 to 6.

3. BASE BLEED

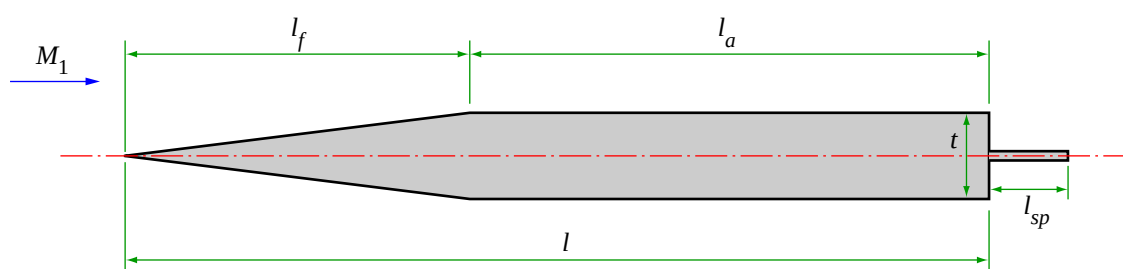
The use of base bleed as a means of reducing base drag has most commonly been applied to bodies of revolution (projectiles, artillery shells *etc.*). Its application to flat-based aerofoils or flat plates, especially at subsonic speeds, has had little attention (References 20 to 22). The reason for this is that in practice any reductions in base drag using base bleed are, at best, likely to be no more than those obtained by passive means, which by their very nature require no power to operate, see Sections 4 to 6. Nash, in Derivation 5, discusses the work of Wood (Reference 20) using low velocity air bled through the base. The tests show that it is possible to reduce the base drag to a level similar to that for a steady wake. However, in order to obtain the required mass flow with a reasonably low injection velocity, a vent height approaching the base thickness was required. In commenting on that result, Nash notes that “When allowance is made for the equivalent drag of the bleed quantity it seems doubtful whether the net reduction in drag is any greater than could be obtained using a short splitter plate.”, see Section 4. Nash also notes that, although the bleed mass flow did not eliminate the vortex shedding it moved the vortex formation point downstream, away from the trailing edge, an effect similar to that found to reduce base drag in other successful devices.

4. SPLITTER PLATES

A splitter plate is a thin plate mounted in the periodic wake aft of a bluff body as a means of controlling the periodicity. Roshko (Reference 16) in the mid-1950s, and later workers, demonstrated the splitter plate's potential for reducing the drag of bluff bodies, such as circular cylinders and flat plates mounted normal to the flow. Based on that work, splitter plates have been shown to be similarly beneficial for the case of interest here, *i.e.* when fitted to the base of blunt flat plates aligned with the flow, as in Sketch 4.1. The presence of the splitter plate has an ameliorating effect on the wake periodicity and, if the plate is sufficiently long, the separated flow on both sides of the plate would be expected to reattach to the plate, suppressing the periodicity and producing a flow similar to that aft of a rearward facing step. The effects of splitter plates on base drag, Strouhal number and reattachment length are considered in Sections 4.1, 4.2 and 4.3, respectively.

4.1 Effect on Base Drag

As part of their investigation into two-dimensional base flows, Nash *et al.* (Derivation 4) looked at the effect of a splitter plate on the wake and base drag of their blunted flat plate model, see Section B3 of Appendix B to ESDU 10016 for details of the model, test conditions and measurements. The general arrangement of the model with a splitter plate is shown in Sketch 4.1.



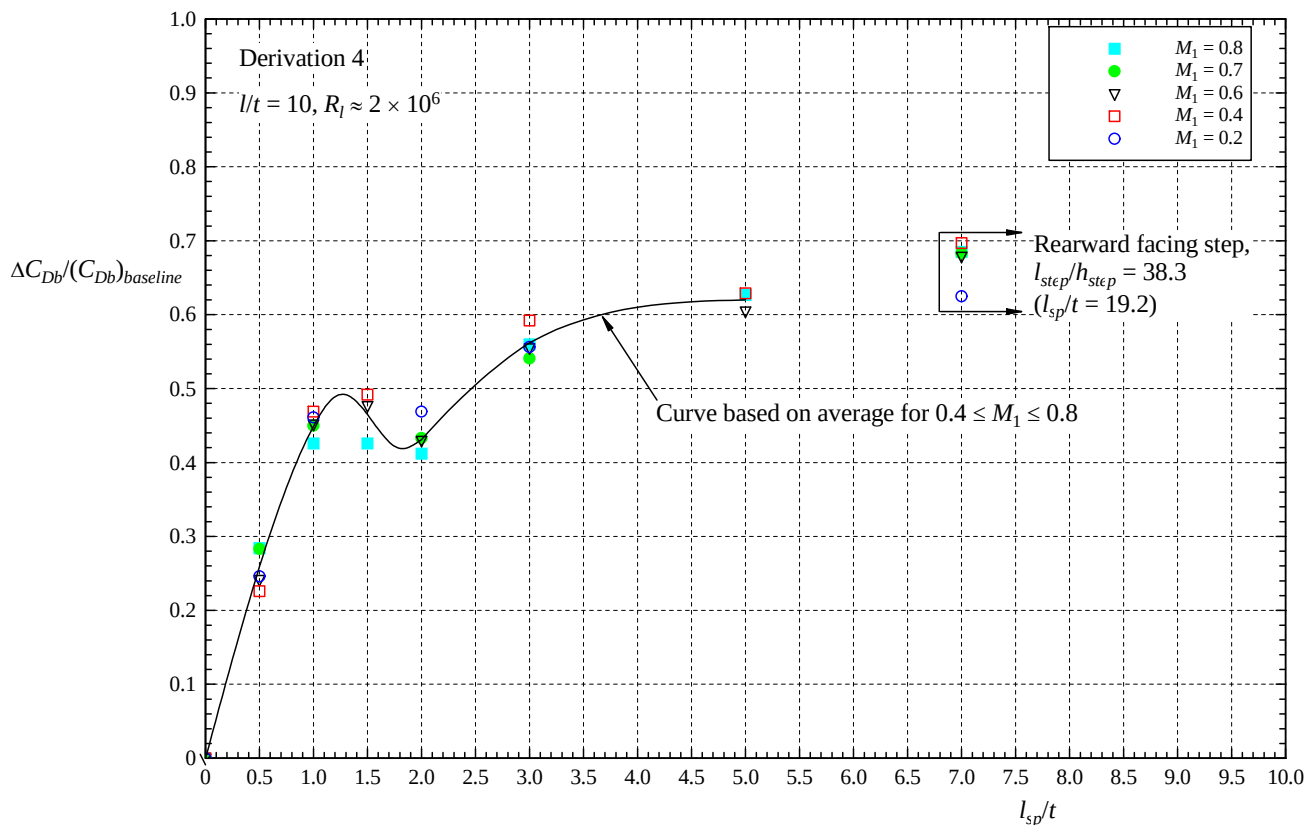
Sketch 4.1 Model layout with splitter plate

Six lengths of thin ($\approx 0.06t$) splitter plate were used with the $l/t = 10$ model, giving $l_{sp}/t = 0.5, 1.0, 1.5, 2.0, 3.0$ and 5.0 . The larger values of l_{sp}/t represent splitter plates that are long compared to the length of the basic plate and would be impracticable. The Mach numbers for the tests covered the range $0.2 \leq M_1 \leq 1.12$, as for the tests without splitter plates. The data for the subsonic range $0.2 \leq M_1 \leq 0.8$ were analysed to determine the reduction in base drag coefficient, ΔC_{Db} , due to the use of each splitter plate, and the results are presented in Sketch 4.2 as $\Delta C_{Db}/(C_{Db})_{baseline}$ against l_{sp}/t , where

$$\Delta C_{Db} = (C_{Db})_{baseline} - C_{Db}. \quad (4.1)$$

In Equation (4.1) C_{Db} is the base drag coefficient with the device and $(C_{Db})_{baseline}$ is the base drag coefficient for the baseline case (*i.e.* the blunted trailing edge).

Nash *et al.* also tested a rearward facing step in which the lower half of the model base (of thickness $t = 0.6$ in.) was extended aft by 11.5 in., terminating in a sharp base with a chamfered lower edge to avoid the introduction of additional base effects. The step therefore had a height $h_{step} = 0.3$ in., *i.e.* $t/2$, and length $l_{step} = 11.5$ in., giving $l_{step}/h_{step} = 38.3$, which can be considered to be equivalent to a splitter plate with $l_{step}/t = 19.2$, with re-attached shear layers. The base pressure coefficients for the step and blunt base (baseline) were used to give the corresponding values of $\Delta C_{Db}/(C_{Db})_{baseline}$ shown in Sketch 4.2.

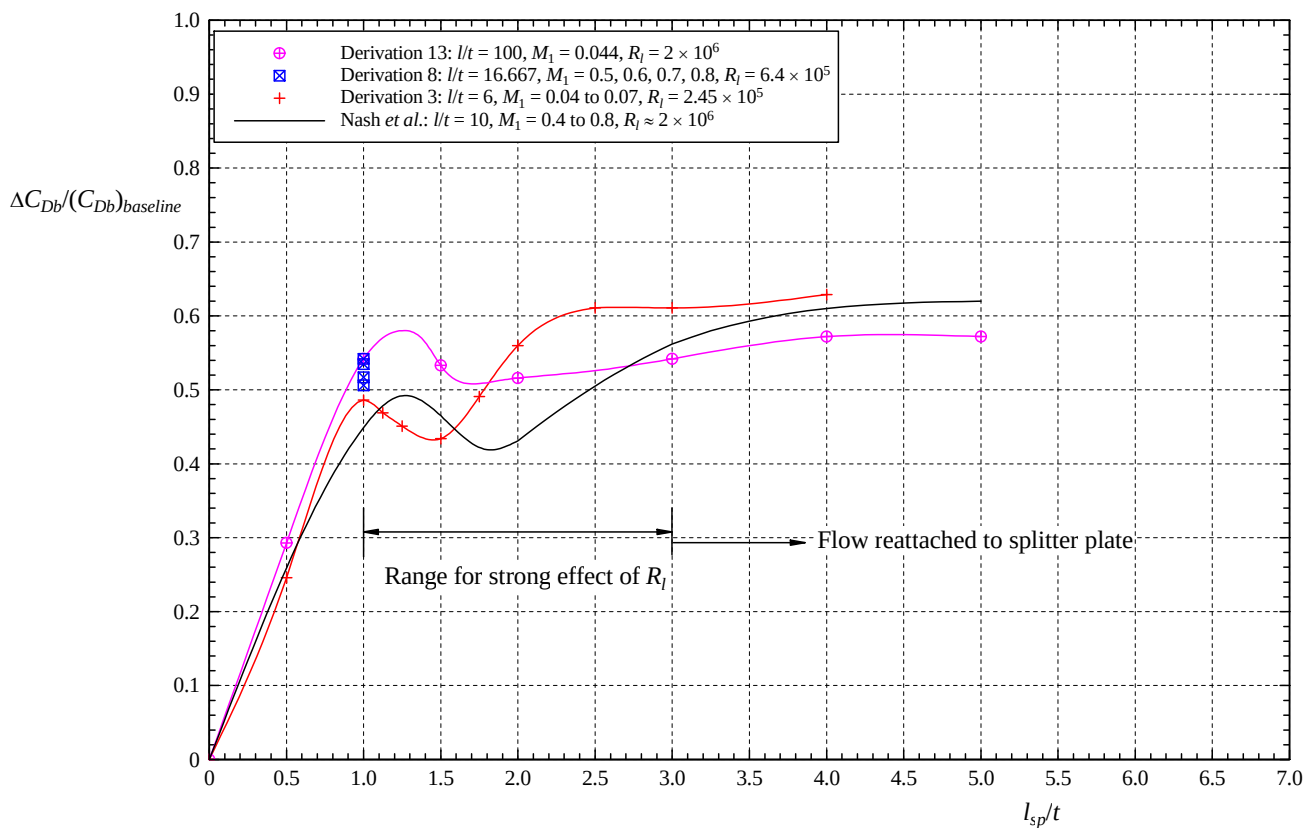


Sketch 4.2 Base drag reduction due to splitter plates (Derivation 4)

From Sketch 4.2 it is seen that:

- The percentage drag reduction due to a splitter plate with a given value of l_{sp}/t is substantially independent of flow Mach number for the range presented, the small scatter with M_1 showing no consistent trends.
- If the mean values of $\Delta C_{Db}/(C_{Db})_{baseline}$ at each value of l_{sp}/t are taken, they are well represented by the solid curve. From the trends in that curve it can be surmised that there are two main flow regimes, one for short splitter plates ($l_{sp}/t \leq 1$) and another for long splitter plates ($l_{sp}/t \geq 2$), joined by an intermediate regime ($1 < l_{sp}/t < 2$). In Derivation 4, Nash *et al.* use Schlieren images to deduce that the main effect of the short plates is to move the point of vortex formation aft of the base by about l_{sp} . Moreover, little sign of periodicity was seen in the free shear layers flowing over the short splitter plates. Over the intermediate range of splitter plates a change in the base flow characteristics takes place. For the long splitter plates, weak periodic disturbances were observed in the free shear layers immediately behind the base before the flows impinged or reattached to the splitter plate further aft, see Section 4.2 later.
- The general trends in the solid curve indicate a very significant base drag reduction, around 45%, for a splitter plate length equal to the base thickness, $l_{sp}/t = 1$. The potential gains from increase in l_{sp}/t beyond 1 are seen to be less dramatic, giving a base drag reduction of about 62% for the longest plate, with $l_{sp}/t = 5$. If the data for the rearward facing step are taken into consideration, it is deduced that a very long splitter plate, with $l_{sp}/t \approx 20$, say, would be required to obtain the likely maximum possible base drag reduction, approaching 70%. This is further substantiated in tests by Arie and Rouse (Reference 18) using a splitter plate attached to a flat plate normal to the stream, which suggested that to achieve completely steady reattachment the length of the splitter plate needed to be about ten times the height of the plate, with base pressure unchanged by further increases in splitter plate length.

Similar data to those shown in Sketch 4.2 are available from Derivations 3, 8 and 13. Of those, the low-speed tests by Bearman (Derivation 3) and Jodai *et al.* (Derivation 13) involved a range of splitter plate lengths, up to $l_{sp}/t = 4$ and 5, respectively, while the high subsonic speed tests by Pollock (Derivation 8) used only one, $l_{sp}/t = 1$. In all three tests the models spanned the tunnel walls, so that the flow could be considered to be essentially two dimensional. The models themselves were very similar in that they all had a rounded or sharp forward section followed by a flat plate with a blunt base, like that shown in Sketch 4.1. The one major difference was in relation to the model length, giving $l/t = 6$, 16.667 and 100 for Derivations 3, 8 and 13 respectively. The test data, analysed like those for Sketch 4.2, are shown in Sketch 4.3 together with the mean line for the Nash *et al.* (Derivation 4) data taken from Sketch 4.2 for comparison.



Sketch 4.3 Additional data for base drag reduction due to splitter plates (Derivations 3, 8 and 13)

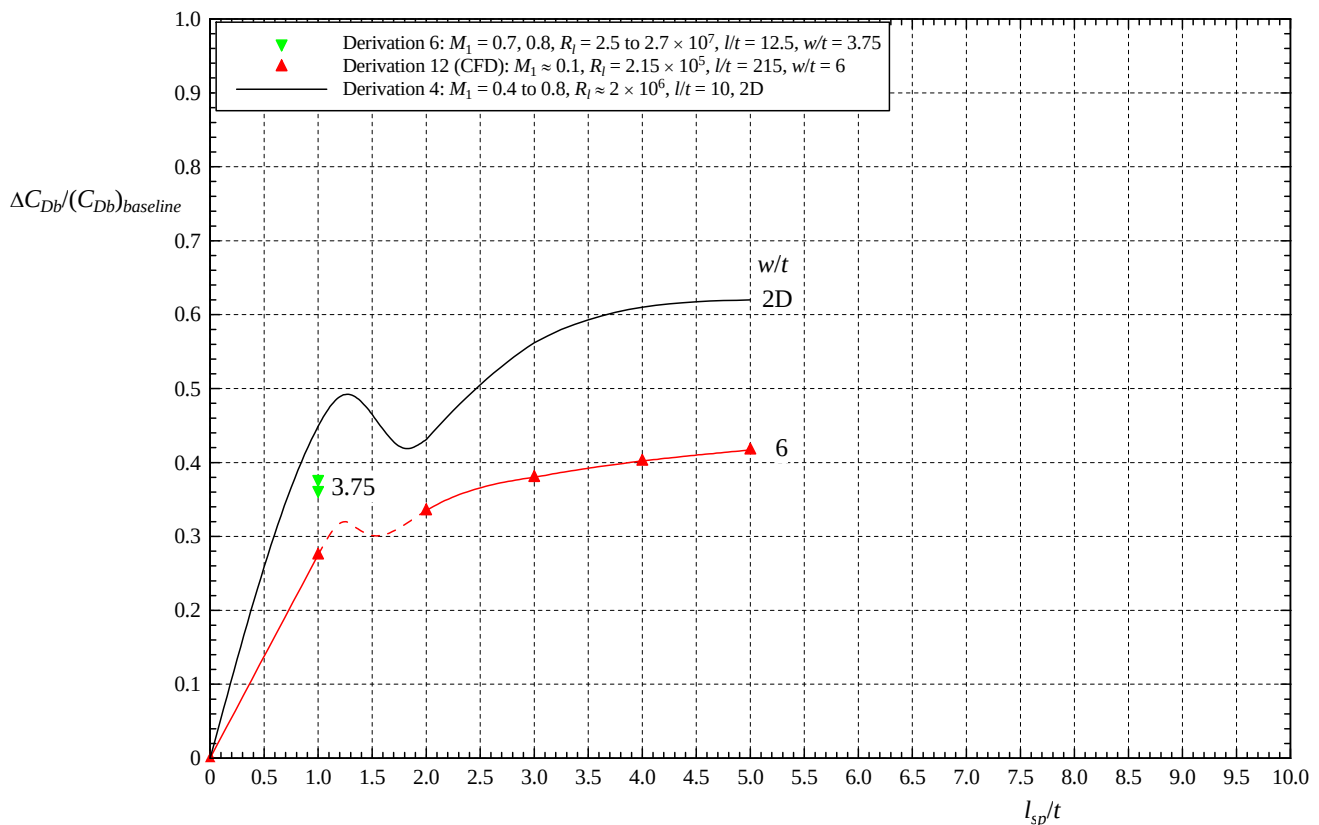
From Sketch 4.3 it is seen that:

- The variation of $\Delta C_{Db}/(C_{Db})_{baseline}$ with l_{sp}/t for the additional data is very similar to that for the data of Nash *et al.* in Sketch 4.2. In particular, the maxima and minima occur in the (intermediate) range $1 \leq l_{sp}/t \leq 2$. The greater number of splitter plates over that range used in Derivation 3 allows a clearer identification of the maximum and minimum points for those tests.
- The largest differences between the curves occur roughly over the range $1 \leq l_{sp}/t \leq 2$. This covers much of the region over which Reynolds number effects are greatest, as suggested in Derivation 3. That might explain the differences between the curves for the data from Derivations 3 and 4, which relate to nearly an order of magnitude difference in R_l (2×10^6 and 2.45×10^5) at not too dissimilar values of l/t (10 and 6), ignoring any possible Mach number effect. Also, the differences between the curves for the data from Derivations 4 and 13 with the same value of R_l (2×10^6) might be explained by the order of magnitude difference in l/t (10 and 100).

iii) The curves tend to a value of $\Delta C_{Db}/(C_{Db})_{baseline} \approx 0.6$ for $l_{sp}/t \geq 3$. It will be seen in Section 4.2 that the separated shear flows tend to reattach to the splitter plate for $l_{sp}/t \geq 3$.

Notwithstanding the differences between the various curves in Sketch 4.3, it is evident that there is little to be gained by using a splitter plate longer than the base thickness. Therefore $l_{sp}/t = 1$ has been almost universally accepted as an “optimum” value. (This value also avoids the use of impractically long splitter plates.)

The data in Sketch 4.3 relate to two-dimensional flow (models spanning wind-tunnel walls). Data from Derivations 6 and 12 indicate significant effects of three-dimensional flow, as shown in Sketch 4.4.



Sketch 4.4 Three-dimensional effects

The Direct Numerical Simulations (DNS) by Yao and Sandham (Derivation 12) concern the trailing-edge flow over a long ($l/t = 215$) flat plate with a blunt base having $w/t = 6$, see Section B4. of Appendix B to ESDU 10016 for more details. The calculations were for a low speed, $M_1 \approx 0.1$, flow at a Reynolds number $R_l = 2.15 \times 10^5$, with splitter plate lengths giving $l_{sp}/t = 1, 2, 3, 4$ and 5. It is seen that the trends of the data are remarkably similar to those from the two-dimensional tests of Derivation 4. However, three-dimensional effects, coupled with the fact that R_l is an order of magnitude lower and l/t an order of magnitude higher than those for Derivation 4, ensure that the relative reduction in base drag for the data from Derivation 12 is lower, by a factor of roughly 0.65.

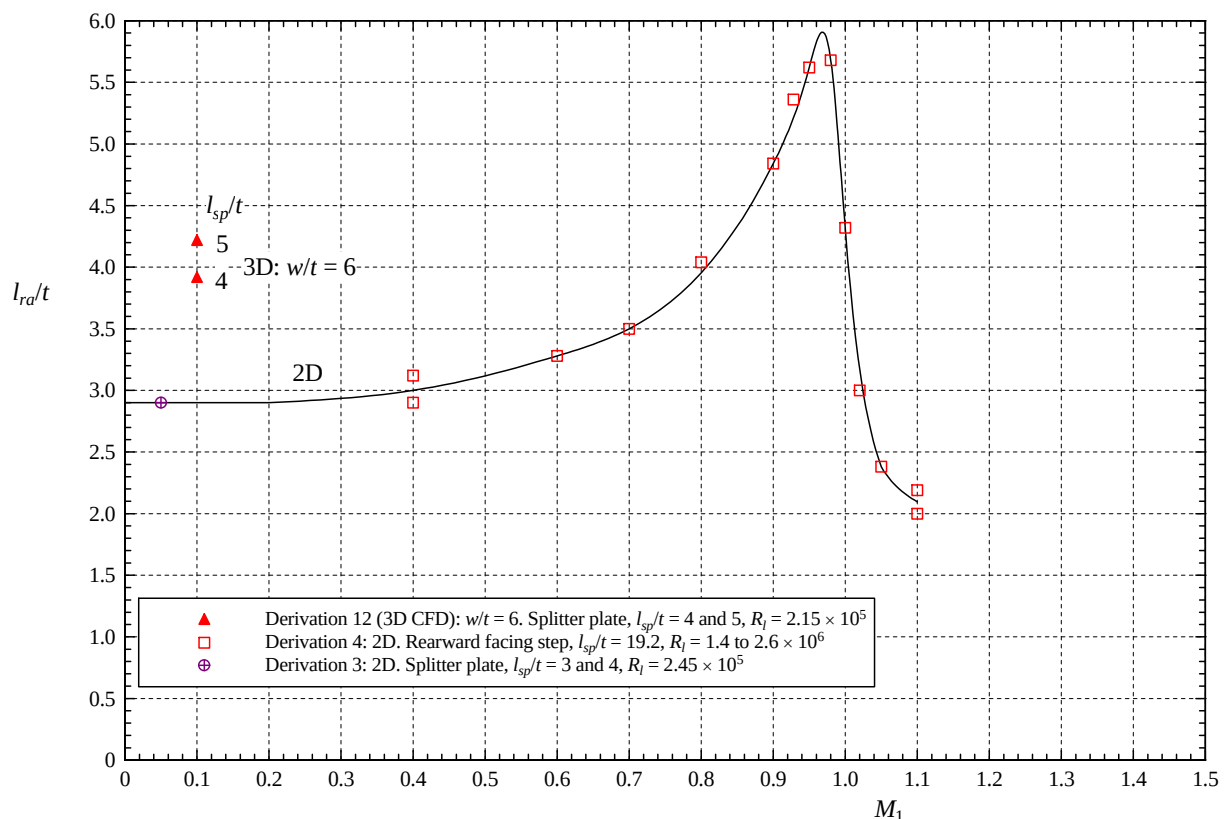
The other data in Sketch 4.4, from Derivation 6, are for flight tests of a large rectangular panel mounted centrally beneath the fuselage of a Lockheed F-104 Starfighter, see Section B4. of Appendix B to ESDU 10016 for more details. The panel had $l/t = 12.5$, with a flat base giving $w/t = 3.75$. The flight Mach numbers were $M_1 = 0.7$ and 0.8 at a Reynolds number $R_l = 2.5$ to 2.7×10^7 . A single splitter plate, with $l_{sp}/t = 1$ (the “optimum” referred to earlier with regard to Sketch 4.3) was used. It is seen that, relative

to the 2D curve from Derivation 4, the effect of three-dimensional flow produces a smaller decrease in $\Delta C_{Db}/(C_{Db})_{baseline}$ than that shown by the DNS data of Derivation 12, which relate to a larger value of w/t . That, coupled with the order of magnitude higher value of R_l , gives a higher factor of about 0.82 on the 2D value for base drag reduction*.

From these data, which are few in number but wide ranging in l/t and R_l , it is not possible to draw any firm conclusions other than that three-dimensional effects appear to be beneficial in terms of the potential base drag reduction using a splitter plate, just as they were for the no splitter plate case in Section B4. of Appendix B to ESDU 10016.

4.2 Reattachment Length

Very few data are available concerning the length, l_{ra} , aft of the base, for reattachment of the separated shear flows to the splitter plate for two-dimensional flows. Bearman (Derivation 3) studied the flow patterns on the splitter plates used in his low-speed, low Reynolds number tests by means of a surface oil film. Flow reattachment was found only for the two long plates, with $l_{sp}/t = 3$ and 4. In each case a reattachment at $l_{ra}/t = 2.9$ was found. The only other data that are relevant pertain to the flow over a long rearward facing step, tested by Nash *et al.* (Derivation 4) and referred to earlier with regard to Sketch 4.2. Here again the surface oil film technique was used to determine the reattachment point variation with test Mach number. The results, for $M_1 = 0.4$ to 1.1 are shown in Sketch 4.5.



Sketch 4.5 Flow reattachment point variation with Mach number

* Although the drag reduction factor appears to be generally less than that for 2D flow, it should be remembered that the 3D effects would already have reduced the baseline values in Derivations 6 and 12 below those for 2D flow, see Sketch B4.1 in Appendix B of ESDU 10016.

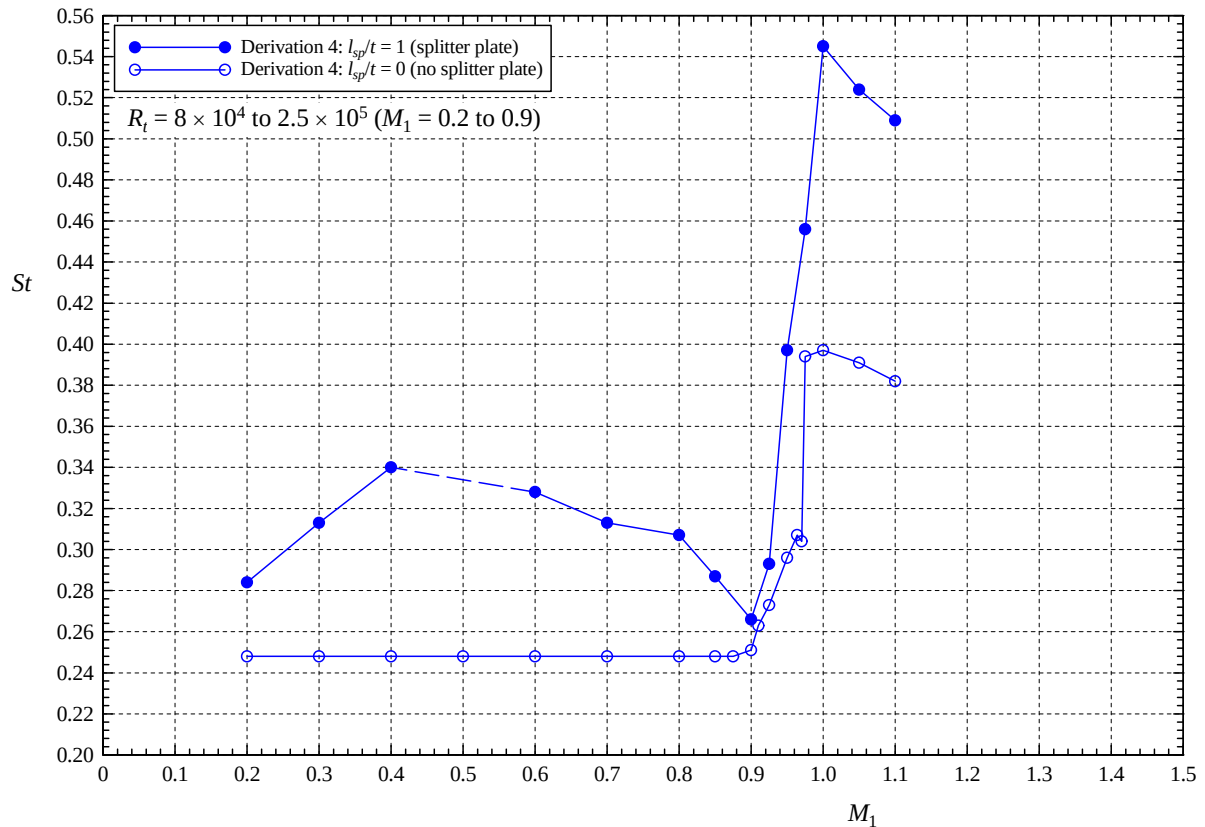
It is seen that the low-speed data for splitter plates from Derivation 3 plot as a natural extrapolation from the high-speed data for a rearward facing step from Derivation 4. Over the subsonic range of interest here, l_{ra}/t increases from about 3 at low speeds up to 4 at $M_1 = 0.8$, increasing thereafter to a maximum of about 6 close to $M_1 = 1$, falling steeply again to about 2 at $M_1 = 1.1$. The variation of l_{ra}/t with M_1 up to $M_1 \approx 0.9$ is closely represented by

$$l_{ra}/t = 2.9/(1 - M_1^2)^{0.3}. \quad (4.2)$$

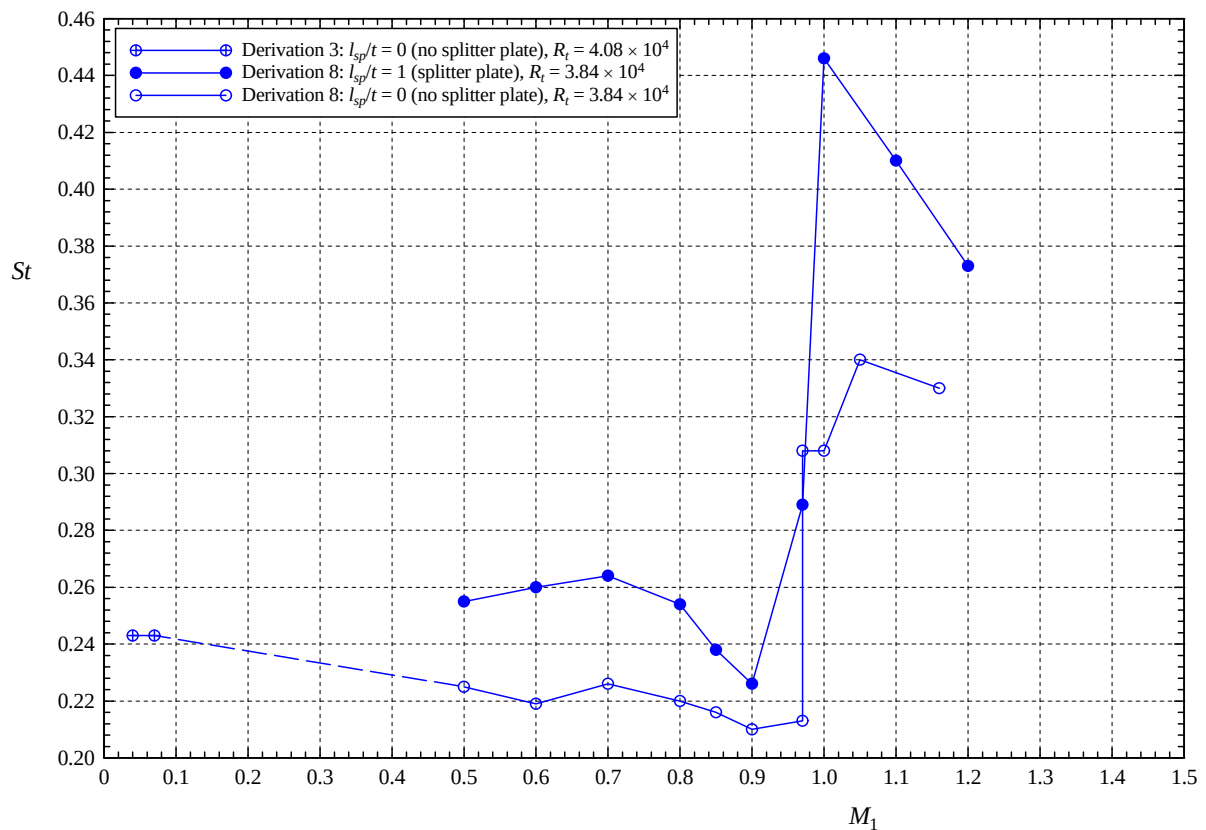
The only data for three-dimensional flow are the low-speed 3D CFD simulations by Yao and Sandham (Derivation 12) on a plate with $w/t = 6$, where flow reattachment for the two long splitter plates with $l_{sp}/t = 4$ and 5 gave $l_{ra}/t = 3.9$ and 4.2, respectively. Yao and Sandham attribute the discrepancy between their simulations and $l_{ra}/t = 2.9$ from Bearman's tests to the large difference in Reynolds number based on base thickness, with $R_t = 10^3$ in their simulations compared to 4.08×10^4 in Bearman's tests. Three-dimensional effects on their own might be expected to reduce l_{ra}/t , as evidenced by the trends in the low-speed flow visualisation tests on cavities of large length/depth ratio and variable width/depth ratio by Panteny (Reference 26), see Sketch 4.19 in ESDU 02008 (Reference 28).

4.3 Effect on Strouhal Number

The frequency of vortex shedding, and its variation with Mach number for the blunt base and with various splitter plates was determined in the tests by Nash *et al.* (Derivation 4) and Pollock (Derivation 8). Nash *et al.* used a stroboscope in conjunction with a Schlieren system to determine the frequency, while Pollock used a light sensitive diode with its output fed into an oscilloscope. The resulting plots of the variation of Strouhal number, $St (= f_v t / U_1)$, with Mach number, M_1 , without and with a splitter plate having $l_{sp}/t = 1$, are presented in Sketch 4.6(a) for Derivation 4 and Sketch 4.6(b) for Derivation 8. Also shown in Sketch 4.6(b) is the value of St from Bearman's low-speed tests (Derivation 3) for his model without the splitter plate.



(a) Derivation 4



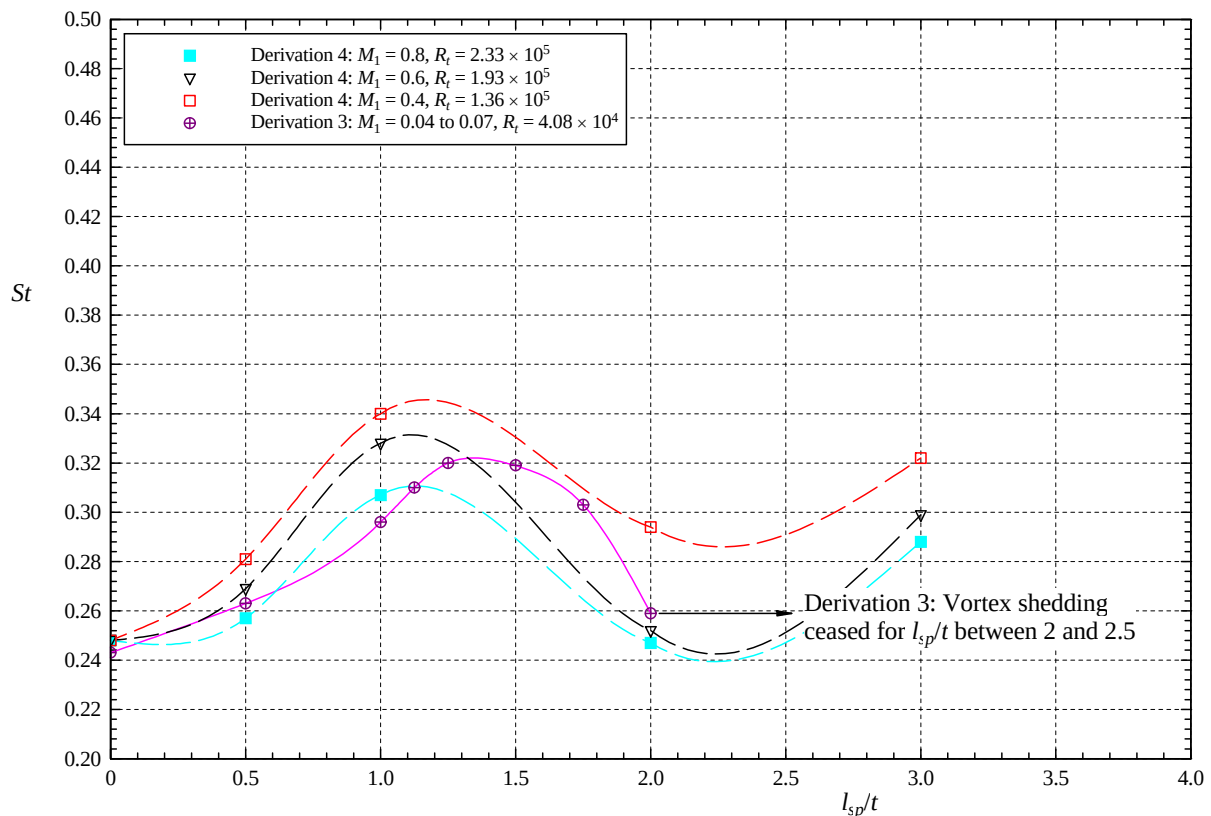
(b) Derivation 8

Sketch 4.6 Effect of splitter plate on Strouhal number variation with Mach number

For the tests with no splitter plate the variation of St with M_1 is different according to whether R_t varies with M_1 or not. The combination of the data from Derivations 3 and 8 for nearly constant R_t ($\approx 4 \times 10^4$) in Sketch 4.6(b) suggests that St decreases steadily as M_1 is increased up to about 0.9. The data from Derivation 4, shown in Sketch 4.6(a), are for tests in which R_t increased with increase in M_1 (from 8×10^4 at $M_1 = 0.2$ to 2.5×10^5 at $M_1 = 0.9$). For those tests St is invariant with increase in M_1 up to 0.9.

For the case with the splitter plate, the Strouhal number at a given Mach number is greater than that without the splitter plate, for the range of test Mach numbers. In the subsonic range, St increases with increase in M_1 up to a certain value ($M_1 = 0.4$ for Derivation 4 and $M_1 = 0.7$ for Derivation 8) and decreases thereafter to become only slightly larger than the value for no splitter plate at $M_1 = 0.9$. As with the case for no splitter plate, St increases sharply above $M_1 = 0.9$ to a maximum at 1 (roughly 100% greater than that at $M_1 = 0.9$), to decrease slowly again in the low supersonic range. In Sketch 4.6(a), the broken line between $M_1 = 0.4$ and 0.6 is explained in Derivation 4 as representing a region over which, although wake periodicity was present, it was difficult to determine the predominant frequency.

A range of splitter plate lengths was tested by Nash *et al.* in Derivation 4 and Bearman in Derivation 3, and both determined the variation of St with l_{sp}/t , albeit at widely different Mach numbers, and using different techniques – Bearman analysed the fluctuating voltage output of a hot wire in the wake. Nevertheless, a comparison of the two sets of data is illuminating, see Sketch 4.7.



Sketch 4.7 Effect of splitter plate length on Strouhal number

The data from Derivation 4 are presented for three Mach numbers covering a wide subsonic range, *i.e.* $M_1 = 0.4, 0.6$ and 0.8 . The low-speed ($M_1 \approx 0.05$) data from Derivation 3 include a number of values of l_{sp}/t in the range from 1 to 2, allowing a more detailed variation over that range than the data from Derivation 4. It is seen that while there is a small effect of Mach number at a given value of l_{sp}/t , as typified by the variation shown in Sketch 4.6(a), the variation of St with l_{sp}/t is very similar from both the low-speed