Performance of Small Skin Friction Balances at Supersonic Speeds

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Some wind-tunnel tests at supersonic speeds with small commercially available skin friction meters are described. The measurements include different meters of the same type exposed to the same shear stress and comparisons with skin friction coefficients derived from local velocity profiles. The measurements suggest that, in zero pressure gradients, accuracies as high as 1% may be obtained if great care is taken. Frequent repeat tests of a datum skin friction measurement, check static calibrations, and balance inspections are recommended. Accuracies as low as 5-7% are obtained from some tests. These balances are always liable to severe damage from the starting or stopping pressure pulse in supersonic wind tunnels. To alleviate this problem, vent holes have been incorporated in the latest balances, but these introduce significant errors. Some research to optimize this modified design is recommended.

Nomenclature

a,b,c = constants for oo Eqs. (1-3)
ΔC_D = increment in total drag coefficient of a surface owing to a projection or recess
C_f = local skin friction coefficient measured by balance
C_{ft} = local skin priction coefficient estimated from law of wall
C_{f_i} = equivalent incompressible skin friction coefficient $= (1+0.2M_e{}^2)^{1/2} C_f$
d = element diameter, m
h = height of element above datum face, m
H = boundary-layer shape parameter
k = distance of element above center of flexures, m
L = streamwise length of rectangular element, m
M = Mach number
R = freestream unit Reynolds number, m^{-1}
u_τ = friction velocity = $(\tau_w/\rho_w)^{1/2}$, m/sec
u = velocity in x direction in boundary-layer, m/sec
p = static pressure, N/m^2
x = distance downstream from plate leading edge, m
y = distance from wall, m
Δ_u = deviation from logarithmic portion of velocity profile in outer edge of boundary layer, m/sec
δ_2 = boundary-layer momentum thickness, m
$R\delta_2{}^i$ = Reynolds number based on equivalent incompressible boundary-layer kinematic momentum thickness $= R\delta_2(1+0.056M^2)$
ν = kinematic viscosity m/sec
π = wake component of boundary layer
ρ = density, kg/m^3
τ = shear stress, N/m^2

Subscripts

e = edge of boundary layer
w = wall

Introduction

MANY investigators have attempted the direct measurement of local skin friction by surface element balances. References 1-3 give some typical examples. In small pressure gradients large balances may be utilized; such balances are relatively easy to calibrate and require small buoyancy corrections. (Winter and Gaudet used a balance of 368 mm in diameter for their definitive skin friction measurements.[3]) In large pressure gradients small balances must be used; these balances are more difficult to calibrate and the buoyancy corrections may be uncertain.

Small skin friction balances are available commercially‡ which were designed for use in flight and wind tunnel experiments. The object of this investigation was to estimate the accuracy which may be expected in wind tunnel tests in which balances of this type are used. The tests included comparisons of the measured skin friction with estimates derived from the law of the wall for the local velocity profile. The tests also included comparisons of the skin friction indicated by different balances of this type.

II. Experimental Details

A. Skin Friction Balances

The skin friction balances are sensitive force-feedback instruments, which give an output voltage proportional to the shear stress being measured. The feedback circuit ensures that the element remains in a fixed position relative to its housing, so that the gap around the element can be much smaller than that required if the element was allowed to deflect. For a conventional skin friction balance, in which the element is allowed to deflect, significant errors in indicated shear force were observed by Westkaemper.[4] With the null type of balance used for the present tests, errors caused by element displacement cannot occur.

The flexures of the instrument are designed to deflect under the pitching moment $\tau_w(\pi d^2/4)k$, applied by the wall shear stress τ_w, which acts at a distance k above the flexure center. Thus the instrument is insensitive to linear acceleration forces and can be mounted in any position. The instruments also incorporated a self-test coil to monitor changes in balance sensitivity as the tests proceed.

B. Balances Used for Series 1-3 Tests

In the first series of tests, comparisons were made between four balances of type 322B100 having a single range from 0 to 392 N/m^2. In the second series of tests, one of the balances

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‡Supplied by special order from Sundstrand Data Control Inc., Overlake Industrial Park, Redmond, Wash. 98052, USA (formerly Kistler Ltd.). These balances have a good laboratory test specification.

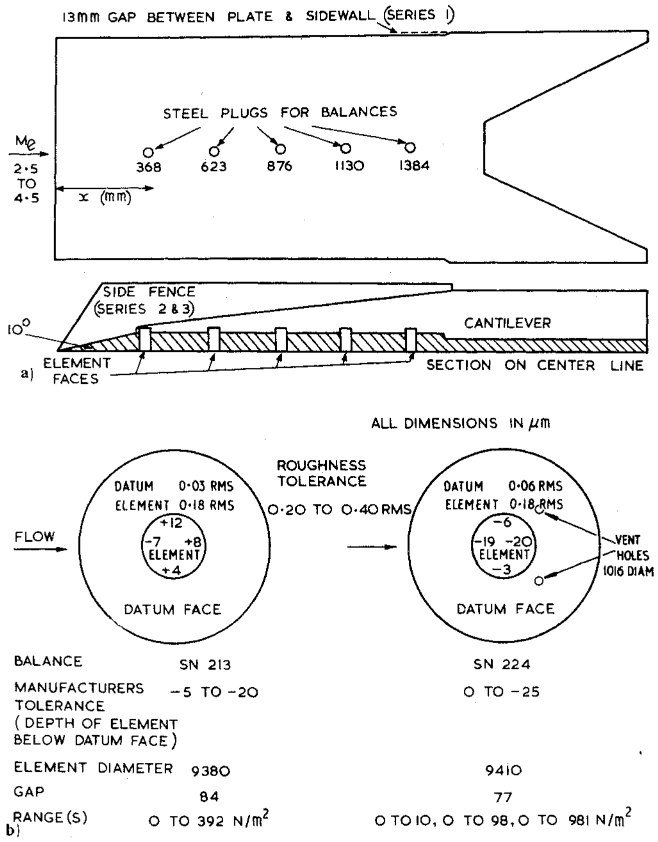

Fig. 1 Skin friction balance tested in RAE 3×4-ft tunnel; a) General arrangement in flate plate; b) Details of skin friction balances.

(SN213) was used to measure skin friction coefficients at low total pressures, where some reduction in accuracy was expected because of the small shear stresses being recorded. In the third series of tests, this balance (SN213) was compared with a new balance of type 322M107 (SN224) loaned to RAE by the DFVLR Gottingen. This balance is supplied with a special amplifier, the gain of which may be altered by a switch to give three alternative ranges for full-scale deflection (FSD): 0-10 N/m^2, 0-98 N/m^2, 0-981 N/m^2. This balance incorporates two vent holes downstream of the element, which communicate with the space under the element. These vent holes are a new feature introduced by the manufacturer in an attempt to reduce the loads perpendicular to the element surface produced by the starting of the tunnel at supersonic speeds.

The balances were tested in the RAE 3×4-ft supersonic tunnel in the large flat plate used for boundary-layer studies[5] (Fig. 1a). Every balance was mounted in a carefully machined steel plug, which could be located in holes drilled in the flat plate at distances of 368, 623, 876, 1130, and 1394 mm from the leading edge. The pressure gradient along the plate was generally small. (These small pressure gradients were, of course, identical for the comparative tests when balances were being interchanged between pairs of holes in the plate or when the vent holes of balance SN224 were sealed.) The pressure gradient term in the two-dimensional momentum balance equation,

$$C_f = 2\mathrm{d}\delta_2/\mathrm{d}x - (2 - M^2 + H)\,\delta_2 \mathrm{d}p/q\mathrm{d}x$$

only varied from about 1×10^{-5} at $M_e = 2.5$ to 3×10^{-5} at $M_e = 4.5$. The back of the plugs containing the balances protruded into the freestream on the upper surface of the flat plate. Here the static pressure was a little higher than on the lower working surface of the plate because of shock waves from the leading edge (beveled at 10°) and the cantilevers on the upper surface which supported the plate. However, there were no passages between the rear of the plugs and the face of the skin friction element which would have allowed leakages.

The unfiltered signal from all of the balances was steady for laminar boundary layers, but became unsteady as the tunnel total pressure increased and transitional or turbulent boundary layers were established. Tests with cover plates over the balance elements (to investigate the origin of changes in zeros) always gave steady, unfiltered signals, which proved that mechanical vibration of the plate made no significant contribution to the total balance signal, as claimed in the instrument specification. Hence the fluctuations in skin friction reading observed as the tunnel total pressure increased must have been aerodynamic in origin, rather than mechanical. Some of the fluctuations may have been caused directly by fluctuations in the tunnel total pressure, although these have now been reduced to an extremely low level,[6] typical values being ±0.1% at $M_e = 4.0$. Reasonably steady readings were obtained with a low-pass filter set to 2 Hz, which had a time constant of about 10 sec.

Balances SN213 and SN224 were carefully inspected when the third series of tests was completed. Figure 1b includes the measurements which might be considered of possible significance for the aerodynamic performance of the balance. At this time the element of balance SN213 protruded from the datum face surrounding it and was outside the instrument specification set by the manufacturer; balance SN224 was within the specification. The surface roughness of both elements was within the specified tolerance, but was much higher than that of the highly polished datum face.

The static calibration of these balances required considerable care. Each balance was mounted vertically and a shear force was applied to the element by weights suspended from a thin thread. It was found that the thickness of the thread made an appreciable difference to the calibration because, even a thin thread applied a small additional pitching moment, as well as a shear force (see Sec. IIA). It was found after some investigation that, if a human hair was used, the manufacturer's calibration could be obtained for balance SN213 and on the two top ranges for balance SN224. The manufacturer's calibration was not obtained for the most sensitive range of balance SN224, and so this range was not used for the tests, although it would have been preferred for the laminar boundary layers.

C. Balance Used for Series 4 Tests

The Series 4 tests were made in the RAE 8×8-ft supersonic wind tunnel with a balance (SN214) of type 322B100 having a single range from 0-392 N/m^2. The balance was calibrated statically using a human hair. The calibration obtained differed from that given by the manufacturers by 2%.

The balance was mounted in the side wall of the working section, where the boundary layer had been previously defined in a detailed investigation.[3] Skin friction measurements were taken over a period of a month while the tunnel was being used for other tests. In this way, the balance provided some indication of its absolute repeatability.

D. Boundary-Layer Probe

A combined pitot and total temperature probe[7] was used to measure the velocity and temperature profiles within the boundary layer during the Series 1 and 2 tests. These profiles were used to help assess the reliability of the local skin friction measurements. No profiles were measured during the Series 3 tests because the time available was severely limited.

E. Test Conditions

The tests in the 3- × 4-ft tunnel covered the Mach number range $M_e = 2.5$-4.5 and unit Reynolds numbers 0.3×10^7-3.0×10^7/m. The tunnel total temperature was adjusted so as to give a calculated plate temperature of 15°C, with a recovery factor of 0.89 for all Mach numbers. For the preliminary series of tests the measured plate temperature was about 23°C. For the main series of tests the tunnel total temperatures were unchanged but the plate temperatures were apparently a little lower, about 18-20°C. Although no alterations had been made to the tunnel or the model, for the main series of tests both the systems for measuring the plate temperature and the tunnel total temperature had cold junctions in a Zerac constant-temperature reference box; this was an improvement on the previous tests.

The tunnel humidity corresponded to a frost point lower than −30°C. A few measurements were taken at the lower pressures with a frost point as high as −25°C, but no significant effect was observed on either the plate temperature or the skin friction readings. In this wind tunnel the frost point improves as the total pressure increases, probably because of the reduction in leaks from the atmosphere into the return circuit. The tests in the 8×8-ft tunnel covered the Mach number range $M_e = 1.35\text{-}2.8$ and unit Reynolds numbers $0.5 \times 10^7\text{-}1.6 \times 10^7/\text{m}$.

The tunnel total temperature varied from 20°C to 36°C. The tunnel nozzle and working section was covered with a thin layer of epoxy resin so that the wall was normally near recovery temperature while the outer shell of the tunnel was vented to the settling chamber and so attained tunnel total temperature. The balance was mounted in a plate 368 mm in diameter, which was not insulated, so that some heat transfer could occur. The frost point was always kept below −30°C.

III. Results

A. Series 1 Tests

Four balances of the same type as SN213 were tested in the boundary-layer investigation reported in Ref. 5. Two of these balances gave consistent and repeatable readings and justified the 1% accuracy in skin friction coefficient claimed at the higher unit Reynolds numbers, where the balances were still only measuring 25% of FSD. The other two balances gave an inferior performance, owing to a combination of rather unsteady readings, lack of repeatability, and wide zero drifts.

The consistency of the data obtained from balance SN213 in the 3×4-ft tunnel is well illustrated by the excellent correlation of skin friction coefficient (C_f) vs momentum thickness Reynolds number, ($R_{\delta 2}$) obtained from the different measurement stations on the plate, for different combinations of $R_{\delta 2}$, and also of shear stress (Fig. 2). This correlation applies over the full range of tests, and agrees quite well with the Winter and Gaudet law,[3] except at low values of $R_{\delta 2}$, where the Winter and Gaudet law would not be expected to work because of variations in the strength of the wake component.[5] In addition, towards the downstream end of the plate at the lower Mach numbers in the Series 1 tests, the boundary-layer development is influenced by shock waves generated by the flow through the gap between the plate and the sidewalls of the tunnel. These shock waves distort the local boundary-layer velocity profiles, which have anomalous values for the wake component (see, e.g., Fig. 4 of Ref. 5), as well as for the local skin friction coefficient which have been excluded from Fig. 2. (This effect was not so serious for the Series 2 and 3 tests because the gap shock waves were almost suppressed by side fences.)

For a number of tests the plug fitted with balance SN213 was rotated through 180° so that the direction of the shear stress acting on the element was reversed. No significant change was then observed in the measured skin friction, which suggested either that the surface imperfections recorded on this balance (Fig. 1b) were not significant aerodynamically or that they were symmetrical, which was rather unlikely. (The static calibration of the balance had previously been shown to be the same in both loading directions.)

The accuracy of the data obtained from the balances may also be assessed indirectly using the velocity profiles. Allen has shown[8] how the Fenter and Stalmach version of the law of the wall[9] may be used to give good estimates for the local skin

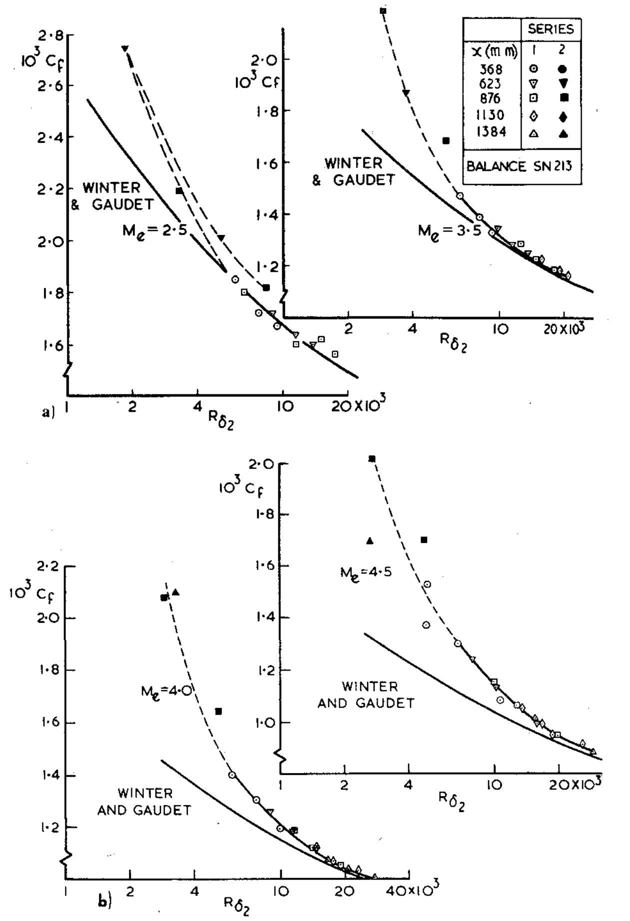

Fig. 2 Correlation of skin friction coefficients from different streamwise positions on plate. a) $M_e = 2.5$ and 3.5. b) $M_e = 4.0$ and 4.5.

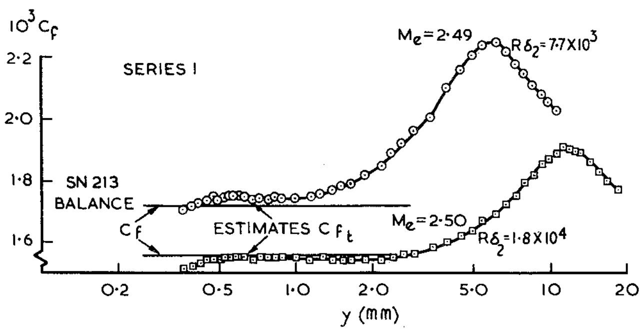

Fig. 3 Comparison of measured skin friction coefficients with estimates from Fenter and Stalmach law of wall.

friction coefficient for adiabatic boundary layers. Figure 3 shows some typical comparisons between the estimated C_{ft} and measured values C_f of the local skin friction coefficients from the wind tunnel tests.

In the wind tunnel experiments at a typical Mach number $M_e = 2.5$, the predicted C_f is about 1% higher than the measured C_f at $R_{\delta 2} = 7.7 \times 10^3$; at $R_{\delta 2} = 1.8 \times 10^4$ the predicted C_f is about 1% lower. [Further comparisons are given in Fig. 4 and also in Fig. 6 of Ref. 5, which show the difference as a % $(C_{ft} - C_f)/C_f$].

The higher values of C_f indicated in Fig. 3 at the edge of the boundary layer occur because the wake component of the velocity profile has not been included in the simple computer program used to calculated C_f from the velocity distribution measured. The maximum value of C_f indicated may be used to derive the strength of the wake component in Fenter and Stalmach coordinates, which uses Coles' law of the wall. In these tests, the strength of the wake component ($\Delta u / u_\tau = 3.2$)

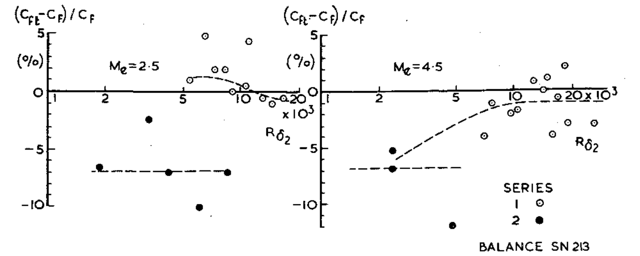

Fig. 4 Further comparison of measured skin friction coefficients with estimates from Fenter and Stalmach law of wall.

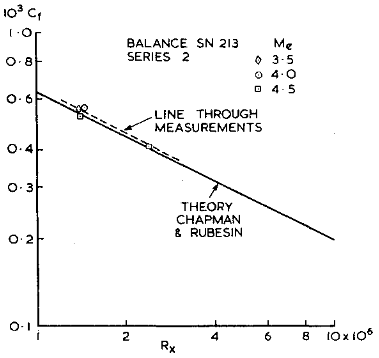

Fig. 5 Comparison between measured and predicted skin friction coefficients for laminar adiabatic boundary layers.

was generally higher than that measured by Coles in a low-speed boundary layer ($\Delta u/u_\tau = 2.75$).

B. Series 2 Tests

Only balance SN213 was available for this brief series of tests. The measurements were made at low unit Reynolds numbers (giving $R_{\delta 2} = 8.4 \times 10^3$) so that the decay of the wake component of the turbulent velocity profiles, observed in the previous tests, could be studied in more detail.

These skin friction measurements for the turbulent boundary-layer are rather scattered, probably because the maximum shear stress measurement was now only 12% FSD. The Series 2 measurements appear to line up tolerably well with the Series 1 measurements (see dotted curves in Fig. 2). Figure 4 shows comparisons of the measured Series 2 skin friction coefficients and those deduced from the Fenter and Stalmach law of the wall. The difference between the estimated and measured skin coefficients $(C_{ft} - C_f)$ is plotted as a percentage of the measured skin friction, against the momentum thickness Reynolds number $(R_{\delta 2})$; the Series 1 results are taken from Fig. 6 of Ref. 5. The measurements suggest the disappointing result that the skin friction meter may have been reading about 7% high for turbulent boundary layers during the Series 2 tests. No explanation for this apparent anomaly is available.

The boundary layer was laminar at the forward position on the plate ($x = 368$ mm) at low unit Reynolds numbers and high Mach numbers, despite the presence of the leading-edge roughness band. The measured laminar skin friction coefficients shown in Fig. 5 are in excellent agreement with values predicted by the Chapman and Rubesin theory,[10] which vary little with Mach number from $M_e = 3.5$ to 4.5. This agreement between measured and predicted laminar skin friction coefficients is satisfactory, particularly if we remember that the balance is now only measuring a maximum shear stress of about 2% FSD. Higher laminar shear stresses, and hence more accurate skin friction coefficients, could be achieved by removing the leading-edge roughness band, e.g., at $M_e = 4.5$ the Reynolds number for transition onset is $R = 3 \times 10^6$ without a roughness band. Tests without a roughness band would be useful in any future evaluation of skin friction meters.

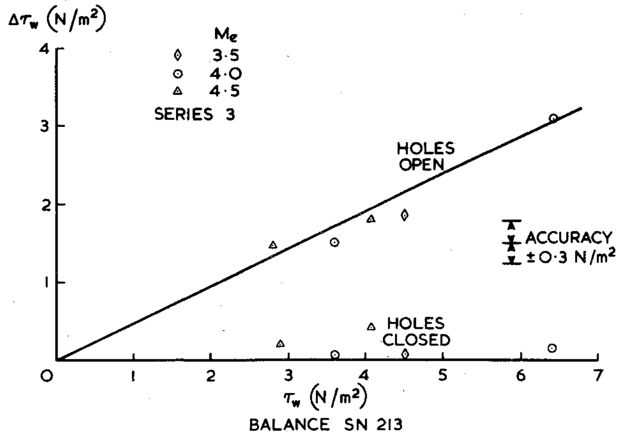

Fig. 6 Differences between shear stresses measured by two balances—laminar boundary layers.

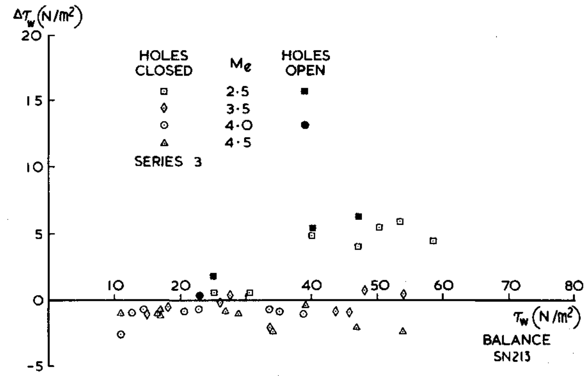

Fig. 7 Difference between shear stresses measured by two balances—turbulent boundary layers.

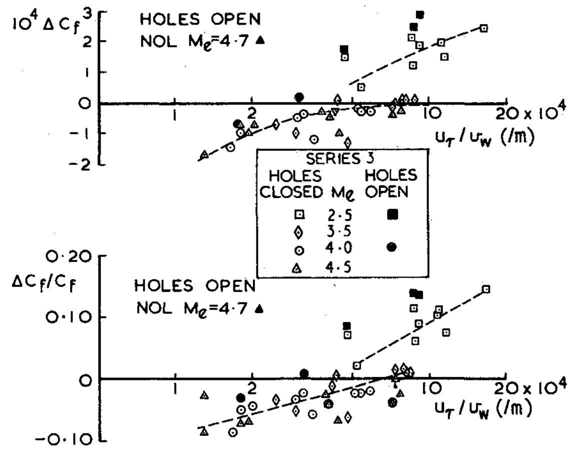

Fig. 8 Possible correlations of balance errors—turbulent boundary layers.

C. Series 3 Tests

Balances SN224 and SN213 were compared during the Series 3 tests; the measurements from balance SN213 were believed to be more reliable and were used as reference. The measurements with a laminar boundary layer showed that the vent holes on balance SN224 introduced a large positive increment relative to balance SN213 (Fig. 6), probably because of a bleed flow induced in through the vent holes and out through the annulus around the element. When these holes were sealed with Sellotape, thus eliminating the bleed flow, the increment in shear stress was reduced to an insignificant level.

The open vent holes also introduce a significant error in the turbulent boundary-layer measurements (Fig. 7). Hence most of these measurements were made with the vent holes covered with Sellotape. Figure 7 shows that appreciable errors still occur, particularly at $M_e = 2.5$ at the higher stresses. Thus, at a stress of 50 N/m^2, balance SN224 reads 5 N/m^2 high at $M_e = 2.5$, but about the correct level for $M_e = 3.5$-4.5. No error in calibration factor or zero drift could explain these results, which were obtained during different runs over a period of several days. Hence the errors must be aerodynamic in origin.

Previous experience suggests that aerodynamic errors may be correlated in terms of the law of the wall unit Reynolds number u_τ/ν_w, which determines the drag of surface imperfections. Figure 8 shows two attempts to correlate the skin friction errors at different Mach numbers using this parameter. The skin friction balance errors are first plotted in terms of the absolute error ΔC_f ((Fig. 8a) and then as the relative error $\Delta C_f/C_f$ (Fig. 8b), which reduces the Mach number dependence a little. Figure 8 also includes a typical example of the error previously measured on balance SN224 in the NOL boundary-layer channel relative to another balance of the same type as balance SN213. (This reference balance agreed reasonably well with the skin friction balance designed and fabricated at NOL.) Figure 8 shows that the errors in balance SN224 in the NOL channel are appreciably higher than in the RAE tests at the same value of u_τ/ν_w and a similar Mach number. The vent holes in balance SN224 were open during the NOL tests and it is possible that small pressure gradients might have magnified the error relative to that observed during the RAE tests.

Figure 8b shows that the error in $\Delta C_f/C_f$ reaches about 10% at $M_e = 2.5$ at $u_\tau/\nu_w = 10 \times 10^4$/m. An error of this magnitude could be produced by an upward displacement of the element of balance SN224 relative to the datum face of 26μm, according to the experiments of O'Donnell et al.[11] This displacement is of the same order of magnitude as errors observed during the inspection at the end of the tests (Fig. 1). However the sense of the displacement observed for balance SN224 is below the datum face. According to O'Donnell et al. this displacement should give a reduction in the local skin friction coefficient rather than the increase measured. This small displacement would be of the order of an equivalent roughness Reynolds number of $u_\tau h/\nu_w = 26 \times 10^{-6} \times 10^5 = 2.6$. Hence, we might expect that the surface imperfections would all be within the viscous sublayer ($u_\tau h/\nu_w < 4$). However, recent measurements[13] show drag penalties due to small excrescences down to values of $u_\tau h/\nu_w = 12$ at $M_e = 2.8$. Thus, a roughness drag penalty might explain these measurements. It should be recalled that the present balances are moment measuring devices, whereas O'Donnell's balance was sensitive only to axial forces. hence, the characteristics of these two balances under conditions of misalighment need not be similar.

It is interesting to note that, at subsonic speeds, Wieghardt found a total drag penalty ΔC_D of the form

$$\Delta C_D = a(h/L)^2 \tag{1}$$

for both circular and rectangular surface elements[12] (Fig. 39). Positive total drag increments were found for both projections and recesses in recent measurements at subsonic and supersonic speeds.[13] These measurements are not necessarily inconsistent with O'Donnell's results[11] for the change in skin friction coefficient ΔC_f on circular elements at supersonic speeds $h/L > 0$ (projection)

$$\Delta C_f = b(h/L) \tag{2}$$

where b is positive, and $h/L < 0$ (recess)

$$\Delta C_f = c(h/L) \tag{3}$$

where c is positive and smaller than b. The drag of the vertical wall or face is included in the drag measurements but is not consistently included in the skin friction measurements.

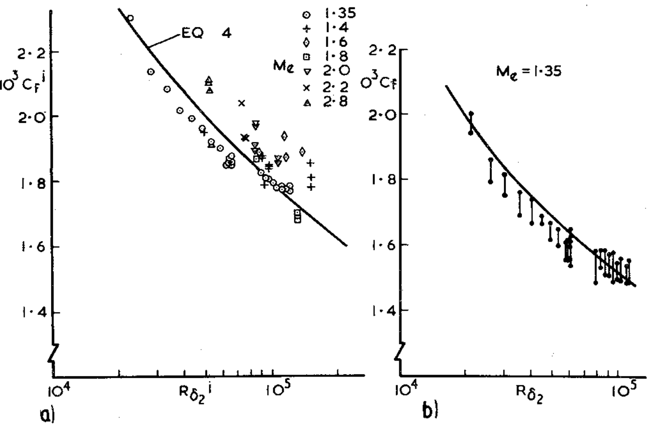

Fig. 9 Skin friction measurements in RAE 8×8 ft tunnel a) Correlation of skin friction coefficients with momentum thickness Reynolds number. b) Variation of C_f indicated by fluctuation of output signal.

D. Series 4 Tests

Figure 9a shows the measurements for balance SN214 mounted on the sidewall of the 8×8-ft wind tunnel. They are plotted in terms of the skin friction coefficient and Reynolds number based on momentum thickness for the equivalent incompressible flow defined in Ref. 3, and the basic skin friction law from Ref. 3 is shown by the line drawn.§ The results shown cover a Mach number range of 1.35-2.8 and for some Mach numbers there is also a range of Reynolds number. The reading of the instrument fluctuated appreciably; maximum and minimum values were recorded and the means of these are shown in Fig. 9a. The results cover a band with a width about 10% of C_f^i. The datum line from Ref. 3 is below the center of the band. The results plotted were derived using a calibration made immediately before the test. If the manufacturer's calibration had been used, values would have been reduced by about 2% and the datum line would then have been close to the center of the band.

The measurements for $M_e = 1.35$, for which a particularly wide Reynolds number range was covered, are shown in more detail in Fig. 9b where the maximum and minimum value noted at each condition is shown. The points at Reynolds number ($R_{\delta 2}$) between 2.5 and 6×10^4 define a line nearly parallel to the datum line and 2-3% below. At higher Reynolds numbers the points cluster along the datum line before finally falling above at the highest Reynolds numbers. This behavior may perhaps correlate with small changes in the total temperature of the tunnel airstream, which may induce temperature gradients in the balance. (As mounted in the 8×8-ft tunnel, the face of the balance is subject to wall recovery temperature.)

The balance sensitivity as indicated by the self-test facility was not entirely constant but the scatter of the results was not reduced by attempting to improve the sensitivity by the use of these checks. During the month of the tests, the zero indicated by the balance varied by up to 2% FSD, though during the course of any one day the change never exceeded 0.2% FSD. The balance was damaged subsequently (Appendix) and has been repaired. The self-test facility now appears to be temperature-sensitive. Over a range of 20°C to 30°C a change of about 0.8% FSD occurs which would imply a similar change in the balance calibration. A static calibration, however, shows no significant variation with temperature though a zero shift of about 0.4% FSD has been noted.

IV. Recommended Test Procedure

The present tests suggest that accurate and consistent measurements may be obtained from these skin friction balances if these recommendations are followed.

§This law is

$$R\delta_{2i} = 0.3894[1 - 4.632(C_{f_i})^{1/2}]e^{0.537(C_{f_i})^{-1/2}}$$

A. Surface Finish

Confirm by a careful inspection that the surface finish and the element position relative to the datum face are within the manufacturer's specification, which seems to be reasonably based.[11] Repeat the inspection subsequently on a routine basis, or if any anomalies in balance performance are suspected. (The inspection should be made with the power on so that the element remains in a fixed position.)

B. Static Calibration

Calibrate the balance before and after every test and compare with the manufacturer's specification. Confirm that the zero readings from the meters do not vary with the attitude.

C. Datum Wind-on Calibration

During every test revert to a datum condition for at least one skin friction measurement. The datum condition for a turbulent boundary layer might be verified by a velocity traverse, from which the local skin friction coefficient could be inferred from the law of the wall.

D. Self-Test Facility

This facility was not used in the Series 1 to 3 tests. However, it was used occasionally during the Series 4 tests (3.4). It is recommended that this facility should be investigated more fully in future tests.

E. Assessment of Vent Hole Errors

The present tests suggest that the vent holes currently provided in the latest balance design seriously compromise its aerodynamic performance, even in a zero pressure gradient. These errors may become larger in a pressure gradient. If the balance has vent holes, and if the tunnel operator is convinced that they must be left open to protect the element (see Appendix), a few comparative tests should always be made with the vent holes sealed to establish the approximate error caused by the vent holes.

F. Assessment of Temperature Errors

The recent measurements on a repaired balance (3.4) suggest that the errors caused by relatively large temperature changes (15°C) may be significant and that these should be measured during the static calibration.

V. Conclusions

The overall impression, obtained from three different series of tests at supersonic speeds with zero pressure gradient, is that small skin friction balances of the same type as SN213 are not very accurate (1% and 7% in Fig. 4, 5% in Fig. 9), although they are easy to use.

For accurate skin friction measurements, an instrument with the correct range must be provided. For all the tests with balance SN213, a range of 0-98 N/m^2 would have been preferred, rather than the range of 0-392 N/m^2 provided. The rapid change in range provided with balance SN224 is an extremely useful feature.

The vent holes in the new instrument introduce serious errors (Fig. 6 and 7). These vent holes have not been optimized so as to provide the maximum protection against starting shocks with a minimum skin friction error, and further development to achieve a better configuration seems essential.

Even with the vent holes sealed there were serious differences between balance 224 and 213 (Fig. 8), which have not yet been satisfactorily explained. The large differences found between balance SN224 and two other balances at NOL may not have been caused solely by the open vent holes. Hence, a thorough datum check on every new balance is advised before use.

Appendix: Failure of Balance SN213 and SN224

When the Series 3 tests were completed, balances SN213 and 224 were first inspected and then installed in the bottom linear of the RAE 4×4 in.-wind tunnel. Both balances were protected by cover plates. Each cover plate incorporated a small venting hole to allow the slow evacuation of air from the skin friction meter; the area of each hole was about half the annular area between the element and the datum face. The balances were not energized for this run, for no readings were required. After the run (at $M_e = 1.4$, p_t = atmospheric pressure) the balances were energized, but failed to operate. The cover plates were removed and both elements found to be protruding from the datum face. Subsequently, the balances were returned to the manufacturers for inspection and repair.

After inspection the manufacturer suggested that the starting or stopping pressure pulse with the tunnel (7000 N/m^2 for this run) had deformed the flexures, even though they should have been protected by the vented cover plates. The maximum safe normal pressure pulse, according to the manufacturer's specification, is 10 times the maximum shear stress, i.e., for balance SN213: 4000 N/m^2, and for balance SN224: 1000 N/m^2.

These limits are consistent with the manufacturer's observation that the flexures of balance SN224 suffered only minor damage, whereas the flexures of balance SN213 were severely damaged. For this run the vent holes on balance SN224 were sealed with Sellotape, as they had been in the majority of tests in the RAE 3×4-ft tunnel. The manufacturer suggested that the flexures would have been undamaged if this Sellotape had been removed.

The implications of these balance failures are serious. If the limitations previously specified must be strictly observed, there will always be a strong probability of breaking these balances in supersonic wind tunnels, unless severe restrictions are placed on the tunnel operations. One restriction might be to start and stop the tunnel at extremely low pressures. The RAE 3×4-ft tunnel is generally started and stopped at the lowest possible pressure to restrict model loads. However, even then the minimum pressure pulse is 17000 N/m^2, well above the specification limits for both balances. Yet this pressure pulse was applied about 100 times to balance SN213 and about 20 times to balance SN224, without any damage being apparent. An alternative restriction would be to cover the balance during the starting and stopping sequence. After starting, when the tunnel Mach number and total pressure are steady, the element could be vented through a valve to the working section static pressure. When these pressures are equal, the cover plate could be withdrawn. The reverse operation would be essential when shutting down. Although this might be easy on the sidewall of a small supersonic tunnel, and has been done in at least one NASA facility, it would be a difficult operation in a large facility like the RAE 3- ×4-ft tunnel.

A long-term solution might be to modify the balance design. If a much larger number of vent holes were incorporated within the balance chamber, the element would not be damaged by the pressure pulse. These vent holes might be sealed intrnally, once conditions are steady. Great care would be needed to ensure that, when the vent holes are sealed, they have a negligible influence on the local skin friction coefficients.

In the author's view, this starting limitation seriously restricts the usefulness of these balances in supersonic wind tunnels and deserves to be more widely appreciated. No severe limitation exists in transonic wind tunnels or in flight, because there the supersonic regions develop progressively, and weak shocks will normally pass relatively slowly over the balance, at Mach numbers in the range $M_e = 1.0\text{-}1.4$.

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