Skin friction balances for large pressure gradients

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Abstract. If floating element balances are used to measure skin friction in a large pressure gradient, the pressure forces on the floating element introduce severe errors. It was shown by Frei (1979) that this deficiency can be overcome by sealing the gap with a liquid, held in place by the surface tension. The forces due to the surface tension can be calculated for a given geometry and pressure field. In the present paper, experiments are described which show that the calculations are correct and that the errors due to surface tension can be made very small compared with the skin friction force.

1 Introduction

Floating element balances have been used many times to measure skin friction in turbulent boundary layers. Surveys of this technique have been given by Rechenberg (1963), by Winter (1977) and, recently, by Acharya et al. (1985). Pressure forces on the element introduce severe errors if a balance of this type is used in a large pressure gradient. It was shown by Frei (1979) that the deficiency can be overcome by sealing the gap between the floating element and the wall with a liquid, held in place by the surface tension. The force due to the surface tension can be calculated for a given geometry and pressure field. In the present paper, experiments are described which show that the calculations are correct and that the errors due to surface tension can be made very small compared with the skin friction force.

2 Description of the balances

The first balance, used by Hirt (1984), is described by Frei and Thomann (1980). It is shown in Fig. 1. The floating element consists of a ring in a circular test section. Two improvements were introduced by Hirt (1984). First, the temperature of the oil surrounding the float d in Fig. 1 was kept constant and slightly above room temperature. This resulted in a marked reduction of the sensitivity of the balance to changes in room temperature. Second, a considerable difficulty to adjust the balance was observed if the three leaf springs e were not precisely in a plane. This difficulty was removed by decreasing the width of two of them so that they were also flexible in the plane of the three leaves.

The second balance was designed by Zurfluh (1984). It is shown in Fig. 2. In this case the floating element a has the shape of a circular disc with a diameter of 60 mm and a thickness of 3 mm. The gap with a width of 0.1 mm was again sealed with a liquid. This liquid seal ring is connected with the container b. The surface of the liquid in this container was kept on the same level as the center of the floating element surface and the air volume above the liquid was connected to the pressure tap c. In two-dimensional flow this resulted in a flat liquid surface at the two stations x = 0 of the liquid seal. A similar container, not shown here, was connected to the pressure taps on the other side of the test section.

Fig. 1. Skin friction balance; a floating element (ring); b electro magnet; c force transducer; d float, submerged in oil; e leaf springs; f centre wall; g liquid, sealing the gap
shown in Fig. 2, was placed on the level of the dummy element \(d\). Both elements are held in place by the lever \(e\) which is supported by two Bendix Free Flex Pivots 6008-800 \(f\). This arrangement could be adjusted to remain in equilibrium when tilted about the \(y\)-axis shown in Fig. 2, which resulted in an extremely low sensitivity of the balance to translational vibrations. A second advantage is the good geometric stability of the system. Before and after one year of use the vertical displacement of the floating element relative to the surrounding wall was within \(\pm 5\ \mu m\). The displacement of the element in the \(x\)-direction was determined with a Schaevitz 050DC-D position transducer \(g\). The output of the transducer was fed into a control system that forced the floating element back to its central position, independent of the force on the element. Details are given by Zurfluh (1984).

Problems were encountered with corrosion at the sharp rim of the floating element. It occurred in the grain boundaries of the light alloy after several months of use. The least troublesome liquid found was propylene glycol with a surface tension \(\alpha = 0.0356\ \text{N/m}\) at 20 °C.

3 Forces on the floating element

An element of the first balance is shown in Fig. 3. The surface of the liquid can support a pressure force that is in equilibrium with the surface tension. This equilibrium leads to

\[
\sin \zeta_1 = \frac{(P_1 - P_{F1})}{\sigma} c_1/2\sigma. 
\]

(3.1)

This expression is based on the assumption of a sharp edge of the element. The conditions for slightly rounded edges are treated by Hirt (1984) where it is shown that a well machined element can be considered as being sharp.

An upper limit for the pressure difference that can be supported is (for \(s_1 \ll b_1\))

\[
(P_1 - P_{F1})_{\text{max}} = \frac{2\sigma}{c_1}. 
\]

(3.2)

For \(\sigma = 0.067\ \text{N/m}\) (glycerine at 20 °C) and \(c_1 = 0.1\ mm\) the resulting pressure difference of 1340 N/m² represents a considerable safety margin for a well designed balance. The deflection \(h_1\) of the surface can be approximated with

\[
h_1 \approx \frac{(P_1 - P_{F1})}{\sigma} c_1^2/8\sigma. 
\]

(3.3)

The friction force on side \((A)-(B)\) is

\[
F_z = l \int_{A}^{B} \tau_w(x) \, dx 
\]

(3.4)

where \(l\) is the spanwise length of the element and \(\tau_w\) is the skin friction. All other forces should be small compared with \(F_z\).

The \(x\)-component of the force due to surface tension \(\sigma\) is

\[
F_x = \sigma l [\cos (\alpha_2 - \beta_2) - \cos (\alpha_1 + \beta_1)]. 
\]

(3.5)

As shown by Frei (1979) this can be transformed into

\[
F_x = \sigma l \left[ \frac{b_2}{c_2} \sqrt{1 - \frac{(P_2 - P_{F2})^2}{2\sigma}} - \frac{b_1}{c_1} \sqrt{1 - \frac{(P_1 - P_{F1})^2}{2\sigma}} \right] + l s_2 (P_2 - P_{F2})/2 + l s_1 (P_1 - P_{F1})/2. 
\]

(3.6)

If gravity is normal to the \(x\)-direction, the \(x\)-component of the pressure force becomes

\[
F_p \approx s_3 (p - P_{F2}) 
\]

(3.7)

where \(p\) is the average pressure on the face \((A)-(B)\).

The shear stress acting on the liquid in the gap will induce a slow motion in the liquid which leads to additional normal forces on the sides \((A)-(D)\) and \((B)-(C)\) in Fig. 3. In the ideal case with \(s_1 = s_2 = s_3 = 0\), \(P_1 - P_{F1} = P_2 - P_{F2}\) and \(b_1 = b_2\), the flow in the two gaps is equal for \(b \ll H\). Due to this symmetry, half of the friction force acting on the gap surface is carried by the ring and half by the casing. This leads to an error of \(b/B = 0.01\) for