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Improved Sensing Element for Skin-Friction Balance Measurements

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An improved skin-friction balance sensing element has been designed and systematically tested. This new element is a nulling, sharp-lipped, parallel-linkage device which was designed to minimize the introduction of extraneous forces into skin-friction measurements. These unwanted forces, which can be sensed by balances of the more conventional nulling, large-lipped, single-pivot design, were investigated in a previous study by the author. That study established that extraneous forces could contaminate skin-friction measurements when using these conventional balances. Comparisons have been made between measurements from the single-pivot and the parallel-linkage balances to demonstrate the improved measuring qualities provided by the latter. These improvements successfully eliminated the extraneous forces, resulting in a balance which is virtually insensitive to gap size and element misalignment.

Nomenclature

a = distance between surface of element and moment center of single-pivot balance
b = moment arm of normal force on element surface
C_f = skin-friction coefficient
C_ℓ = lip-force coefficient
C_N = normal-force coefficient
C_t = total-force coefficient
c = lip thickness of element
D = diameter of sensing element
G = gap size between element and surrounding test surface
M_e = freestream Mach number
Z = misalignment between element surface and surrounding test surface
δ = boundary-layer thickness

Subscripts

av = average value
0 = evaluated at $Z/\delta = 0$

I. Introduction

IN an earlier publication,[1] the present author published the results of a systematic study of potential error sources in skin-friction balance measurements in supersonic flow. In that study, a large skin-friction balance, whose design and construction details are described in Ref. 2, was tested and the results evaluated. That balance was a nulling, single-pivot device similar in operating principle to the small Kistler balance, which is described in Ref. 3, but was much larger to allow systematic variation of geometric parameters. The diameter of the sensing element of this large balance was about 14 times that of the Kistler balance. The geometric parameters which were systematically varied in that study were the size of the gap between the sensing element and the surrounding test surface and the misalignment of the sensing element both above and below the surrounding test surface.

It was proposed and experimentally confirmed in Ref. 1 that the total force acting on the sensing element was composed of three components—i.e., skin friction, lip force, and normal force—and are related in coefficient form by the following equation:

$$C_t = C_f + \left(1 - \frac{c}{2a}\right) C_\ell + \frac{b}{a} C_N$$

The last two terms in this equation are normally assumed to be negligible in most experiments using skin-friction balances. Thus, the total force measured is assumed to be the friction force, and no corrections are applied.

The major conclusion of Ref. 1, however, was that these last two terms are not always negligible, and that errors could, therefore, be introduced into balance measurements which assume their negligibility.

The next logical step in this research program was to redesign the balance in an attempt to minimize these potential errors. A new nulling, parallel-linkage sensing element was thus designed and tested. The purpose of this paper is to report on the results of this test, and to make comparisons between the single-pivot and parallel-linkage designs to demonstrate the improved skin-friction measuring capabilities provided by the new balance.

II. Analysis of the Problem

The results of the earlier study[1] showed that the effects of gap size and element misalignment could result in significant errors in skin-friction measurements when using balances of the single-pivot design. This design is essentially a moment-measuring device which responds to any moment tending to rotate the element in the streamwise direction, and is thus unable to distinguish between the friction force and these extraneous forces.

It was shown in Ref. 1 that the size of these unwanted forces could be significant compared to the size of the friction force. Since these extraneous forces are assumed to be negligible in most skin-friction balance testing, the altered output of the balance could result in erroneous friction drag measurements.

This problem can be illustrated with the aid of Fig. 1, which is taken from Ref. 1. Independent estimates were made of the total, friction, normal, and lip forces acting on the element over a range of element misalignments both above and below the surrounding test surface. The accuracy of these measurements can be ascertained by noting, in the insert of this figure, a comparison between the total force measured by the balance and the sum of these independent estimates of friction, normal, and lip forces.

It can be seen from this figure that at perfect alignment, the error caused by the extraneous lip and normal forces is very

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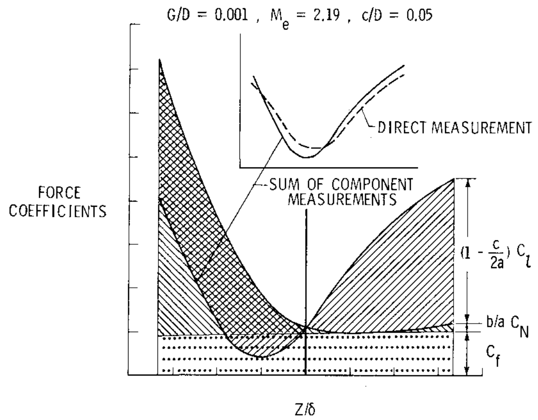

Fig. 1 Results of Ref. 1 using single-pivot balance.

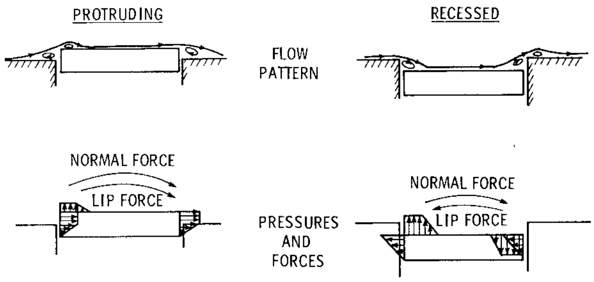

Fig. 2 Misalignment effects on sensing element.

small compared to the friction force. Hence, at perfect alignment, balances of the single-pivot design provide an accurate measurement of friction force. With either positive or negative misalignment, however, the extraneous forces become an increasingly large part of the total force measured by the balance, and eventually completely dominate the friction force.

To illustrate the underlying flow patterns which result in these extraneous forces, Fig. 2 has been prepared (taken from Ref. 4) to show how the flow behaves over an element which is misaligned with respect to the surrounding surface. The pressures created by these flow patterns are illustrated at the bottom of this figure. It is these pressures on the surface and lip of the element which create the moments which erroneously become part of the friction measurement.

These two figures illustrate the benefits of having the element misalignment as small as possible, and also point out the desirability of developing a balance which would not be as sensitive to misalignment as the one tested in Ref. 1. Since the lip force acts in the same plane as the friction force, there appears to be no way of mechanically separating these two forces acting on a single sensing element. Hence, the effort in this study to minimize the lip force has concentrated on reducing the pressures on the lip by adjusting the size of the gaps between the sensing element and the surrounding surface, and by minimizing the area on which these pressures act by reducing the size of the lip around the sensing element.

The normal force, on the other hand, acts on the element surface in a direction perpendicular to the friction force. The moment-measuring nature of the original design caused the sensing element to be sensitive to off-center normal forces. The new sensing element developed in this study is designed to eliminate this normal-force problem by replacing the original sensing element with a parallel-linkage arrangement. A schematic representation of the single-pivot and parallel-linkage designs is shown in Fig. 3. The new element should be sensitive only to streamwise forces; thus, any extraneous forces normal to the element surface should not alter the balance output.

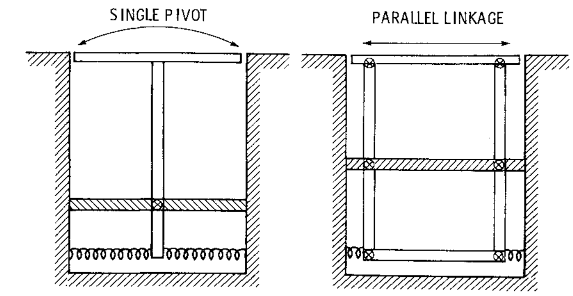

Fig. 3 Sensing element designs.

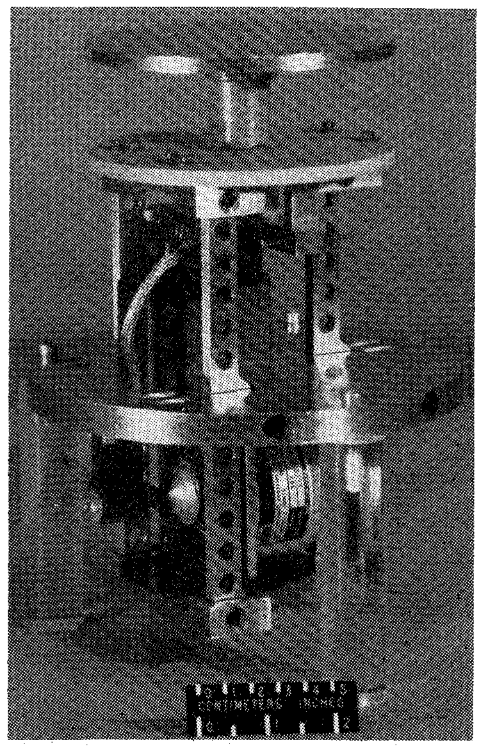

Fig. 4 Parallel-linkage sensing element.

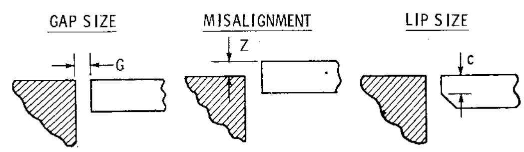

Fig. 5 Geometric variables.

III. New Sensing Element

The skin-friction balance used in this study was, with the exception of the newly designed sensing element, the same as that used in Ref. 1. A photograph of the new parallel-linkage sensing element is shown in Fig. 4. The output of this balance is simply the voltage required to keep the sensing element in the null position. The mechanical and electrical detail of this new element can be found in Ref. 5. Three geometric parameters were systematically varied in this study to investigate their effects on the balance output. These parameters were 1) gap size, 2) misalignment, and 3) lip size, and are illustrated in Fig. 5. The first two parameters were varied to provide data for comparison with that of Ref. 1. The nominal diameter of the floating element was 12.7 cm. Interchangeable elements of slightly different diameter were used to test the effects of gap size. A drive mechanism was used to control the misalignment of the floating element with respect to the surrounding test surface.

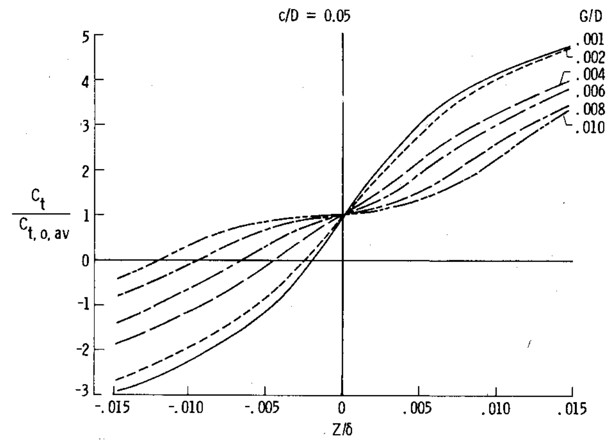

Fig. 6 Effects of misalignment and gap size on total force.

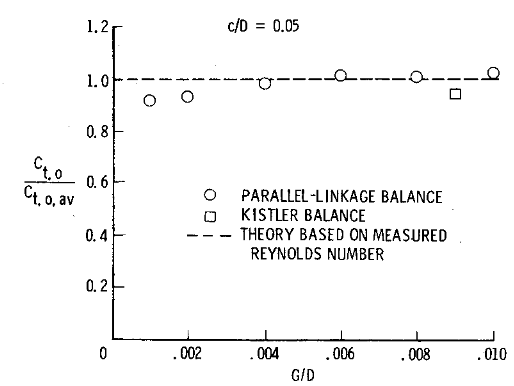

Fig. 7 Effect of gap size on total force at zero misalignment.

The third geometric parameter, lip size, was varied as a result of the Ref. 1 data which showed that lip forces on the element could produce significant errors in the balance measurements. The lip size on the element was varied by progressively beveling the lip at a 45-deg angle, and ranged from the unbeveled lip used in Ref. 1 to a sharp lip.

IV. Wind Tunnel Tests

It was desired to investigate the characteristics of this newly designed balance at test conditions as close to those of Ref. 1 as possible so that the data from the two studies could be directly compared. The wind tunnel used in the earlier study was no longer available for use, so the exact test setup could not be duplicated. Instead, the present test was performed in another tunnel at similar, but not exact, flow conditions. Table 1 compares the test conditions for the present study and those of Ref. 1.

In both studies, the tunnel sidewall was used as the test surface to provide a long run of turbulent flow and a thick boundary layer. The test station was located on the sidewall centerline in about the middle of the test section. Both tests were conducted at adiabatic wall conditions.

V. Effects of Gap Size and Misalignment

Figure 6 shows the effects of misalignment on the balance measurements for different gap sizes at the largest lip thickness. This figure shows that the larger the gap size, the less sensitive the balance was to misalignment. This was a trend which was also noted in Ref. 1. The effect of gap size, however, virtually disappears near zero misalignment.

All coefficients in this and subsequent figures have been normalized by the average of all the zero misalignment balance measurements obtained in this study. This average measurement should be very close to the true skin-friction coefficient for the test conditions of this study, and is used for normalizing so that magnitudes can be more easily assessed.

Table 1 Test conditions

Test	Ref. 1	Present
Tunnel	4-ft SPT	UPWT
Mach number	2.19	2.16
Unit Reynolds number	3.61×10^6/m	3.61×10^6/m
Momentum thickness	0.45 cm	0.48 cm
Boundary-layer thickness	7.6 cm	8.6 cm
Momentum thickness Reynolds number	1.62×10^4	1.71×10^4

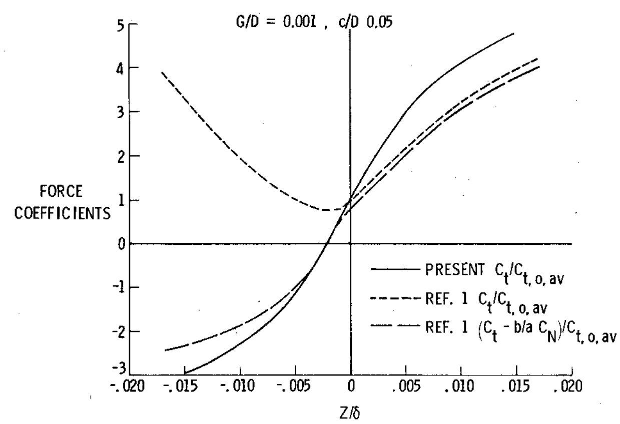

Fig. 8 Comparison of present results with those of Ref. 1.

Figure 7 confirms that these zero misalignment balance measurements taken from Fig. 6 were not a function of gap size. These measurements are also seen to be in good agreement with the theoretical skin friction calculated from a measured momentum thickness Reynolds number and with measurements taken by a small Kistler balance.

VI. Comparison between Present and Ref. 1 Data

The effects of the change in the sensing element design are demonstrated in Fig. 8 by comparing the results obtained in the present study with those of Ref. 1 for the smallest gap size, which was the most sensitive to misalignment errors. Comparing the total-force output of the two balances, the large differences between the trends of the two occur at negative misalignment and are due to the balance results of Ref. 1 being affected by off-center normal forces (Fig. 1), whereas the present results are not. The small increase in sensitivity of the new element of misalignment is caused by the fact that the two large errors, lip force and off-center normal force, which were present in the Ref. 1 data, were somewhat offsetting.

This can be demonstrated by subtracting the normal-force distribution, found in Ref. 1, from the total-force distribution of that balance. The results from the two balances should now be similar since both are now affected only by skin friction and lip forces. This comparison can also be seen in Fig. 8, and shows that the trends of the data from the two balances are indeed very similar. Thus, the new parallel-linkage design has successfully removed the sensitivity of the balance to off-center normal forces.

VII. Effect of Lip Size

In all the results discussed thus far, the data were obtained using elements with the large lip thickness used in the Ref. 1 test. Figure 9 shows the results of reducing this lip thickness. Since this balance is not measuring errors due to off-center normal forces, the error due to misalignment should result from the lip forces. This appears to be the case since reducing the size of the lip produces a corresponding reduction in the sensitivity of this element to misalignment. At zero lip size, there appears to be only negligible sensitivity except for an

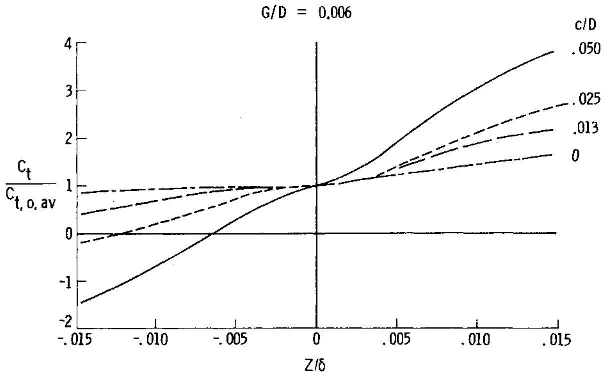

Fig. 9 Effects of misalignment and lip size on total force.

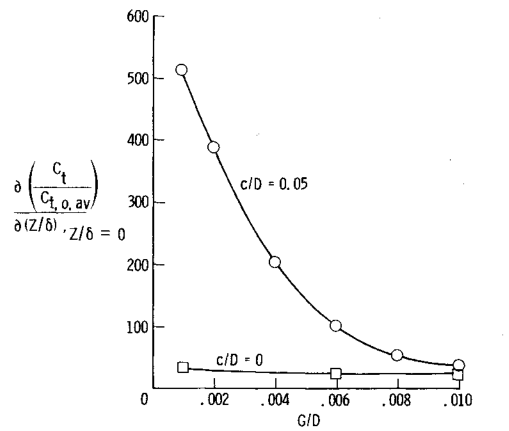

Fig. 10 Balance sensitivity to misalignment near $Z\delta = 0$.

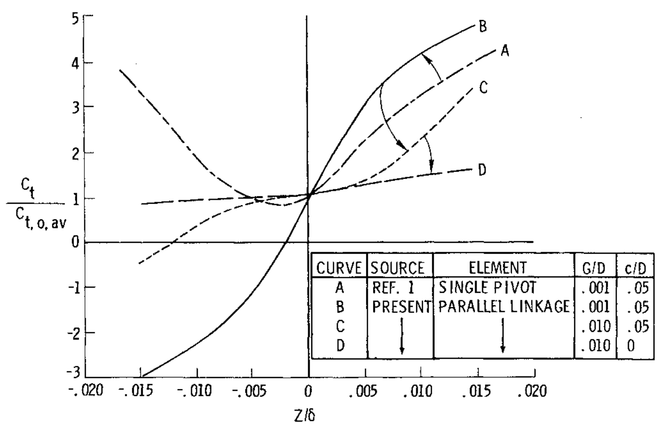

Fig. 11 Summary of improvements.

increase at the largest positive misalignments. This increase is probably due to the dynamic pressure on the part of the element exposed to the flow as the element is protruded into the boundary layer.

The effects of lip size shown in Fig. 9 were obtained for an intermediate gap size. It was found, however, that gap size had a strong effect on the sensitivity of the element to lip forces, and is summarized in Fig. 10. Here, the slopes of the balance output vs misalignment curves at zero misalignment have been plotted as a function of gap size for the largest and smallest lip sizes. These slopes reflect the sensitivity of the element to misalignment in the region where misalignment errors are more likely near perfect alignment. Gap size has a very large effect at the large lip size, but has an almost negligible effect at zero lip size. Hence, the reduction in lip size not only reduced the size of the lip force acting on the element, as could be expected from the reduced area on which the pressures had to act, but also virtually eliminated the effect of gap size on the balance output.

VIII. Summary of Improvements

A summary of the progress which has been made in this study in reducing the sensitivity of skin-friction balance measurements to misalignment can be demonstrated in Fig. 11. Each of the four curves presented in this figure represents a single improvement in measuring qualities, and the difference between the curves represents the improvement caused by a single geometric change.

The difference between curves A and B represents the effect of changing the sensing element design from a single pivot to a parallel linkage, thus eliminating the off-center normal-force effects.

Going from curve B to curve C represents the effect of increasing the gap size. The smallest gaps were found, both in the present study and in that of Ref. 1, to be the most sensitive to misalignment, while the least sensitive were the largest gaps.

Going from curve C to curve D represents the effect of eliminating the lip on the sensing element. Although curve D represents data taken at the largest gap size so it could be directly compared with curve C, data from any of the gap sizes for the sharp lip would have appeared virtually the same as curve D since the effects of gap size were found to be negligible for the sharp-lip data.

It should be emphasized that both the new sensing element design and the reduced lip thickness were needed to achieve this low sensitivity to misalignment and to gap size, as illustrated by curve D. Although sharp-lipped elements were not tested in Ref. 1, results as good as those seen in curve D would not have been attained had they been tested due to off-center normal-force sensitivity of the single-pivot element used in the earlier study.

References

[1]Allen, J. M., "Systematic Study of Error Sources in Supersonic Skin-Friction Balance Measurements," NASA TN D-8291, Oct. 1976.

[2]Fowke, J. G., "Development of Skin-Friction Balance to Investigate Sources of Error in Direct Skin-Friction Measurements," M. S. Thesis, Univ. of Virginia, Charlottesville, Va., June 1969.

[3]Paros, J. M., "Application of the Force-Balance Principle to Pressure and Skin-Friction Sensors," *16th Annual Technical Meeting Proceedings,* Institute Enviromental Sciences, Boston, Mass., April 12-16, 1970, pp. 363-368.

[4]Winter, K. G., "An Outline of the Techniques Available for Measurement of Skin Friction in Turbulent Boundary Layers," *Progress in Aerospace Sciences,* Vol. 18, No. 1, Pergamon Press, New York, 1977, pp. 1-57.

[5]Tcheng, P., "Development of a Servo Transducer for Direct Skin-Friction Measurement," Dept. of Mechanical Engineering and Mechanics, School of Engineering, Old Dominion University, Norfolk, Va., Prepared for NASA Langley Research Center under Research Grant NSG-1079, July 1979.