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Technique for Measuring Side Forces on a Banked Aircraft With a Free-Swiveling Nose Gear

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National Aeronautics
and Space Administration

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Summary

An experimental investigation was conducted at the Langley Research Center to determine a method for towing an aircraft to measure the side forces of a free-swiveling nose gear due to variations in bank angle. An F-106 aircraft and the Space Shuttle orbiter OV-101 were towed to measure side forces on full-size aircraft for bank angles up to 3°. These tests indicate that substantial side forces will occur if an aircraft is rolling on a runway in a banked attitude even when the nose gear is free to swivel. Corotation of a twin-tire nose gear appears to cause a substantial increase in side force due to bank angle compared with a nose gear with independently rotating wheels.

Introduction

It has been observed that a significant amount of differential braking, above that which had been predicted, is required to maintain the correct heading and alignment on the runway during the landing rollout of the Space Shuttle orbiter in the presence of a crosswind. There are a number of factors that can cause side force on an aircraft, and some of these are accentuated on the orbiter. Some of these factors are the side wind itself, runway crown, ply steer, and negative weathercocking. Another factor, perhaps lesser known or understood, that can cause appreciable side force on an aircraft is bank angle with a free-swiveling nose gear. Reference 1 presents a cursory examination of bank angle (roll) as a method of steering a vehicle on the runway when skids are used on the main landing gear. Bank angle can be caused by a crosswind loading the downwind gear more than the upwind gear, or it can be caused by a tire failure or a loss of landing-gear strut pressure. Runway crown can also cause bank angle by loading the downslope gear more than the upslope gear. A further complicating or additive factor in the presence of bank angle is corotation of the nose wheels on a twin-wheel nose gear. More detailed data obtained on a test vehicle with a tricycle landing gear subsequent to the tests presented in this report are published in reference 2, and the effect of corotation is discussed. Because of unacceptably high brake wear rates for the Space Shuttle orbiter, it was desirable to investigate experimentally the side forces due to vehicle bank angle and to obtain values for use in simulators to study the problem and find ways to reduce the effects of these side forces.

This paper presents several methods for towing an F-106 aircraft in an attempt to determine the best procedure for towing the Space Shuttle orbiter to measure experimentally the side forces for bank angles up to 3°. Side-force data from tow tests of both the F-106 and the orbiter OV-101 are presented. Tests of the Space Shuttle orbiter were conducted at the Dryden Flight Research Facility by Arthur M. Whitnah and Carlisle C. Campbell, both from the Johnson Space Center.

Description of Test Vehicles

F-106 Aircraft

An F-106 aircraft hull was used at the Langley Research Center to develop a towing procedure for measuring nose gear side force. A photograph of the F-106 is shown in figure 1. The aircraft engine and other parts had been removed, and the total weight of the vehicle was 14 700 lb. The weight on the nose gear was 4600 lb. Figure 2 is a sketch of the landing-gear spacing for the F-106. Geometric trail on the nose gear, also shown in figure 2, was found in reference 2 to be an important parameter in the development of side force on a free-swiveling nose gear. The F-106 nose gear is not corotating, that is, each nose wheel rotates independently. (It is not forced to rotate at the same speed as the other nose wheel, as would be the case if they were splined to the same rotating axle.) Nose gear steering was disconnected to allow the nose gear to swivel freely.

Bank angle was obtained by reducing the strut charge pressure in the left main gear strut as shown in figure 3. The left main gear strut was stroked 9 in. more than the right main gear to give the vehicle a bank angle of 3°. No attempt was made to assure that the nose gear strut was vertical in the fore and aft plane.

Shuttle Orbiter OV-101

The Shuttle orbiter OV-101 was used at the Dryden Flight Research Facility to measure side forces on the nose gear for bank angles up to $2\frac{1}{4}°$. A photograph of the Shuttle orbiter OV-101 is shown in figure 4. The total weight of the vehicle was 113 131 lb, and the weight on the nose gear was 21 474 lb. Figure 5 is a sketch of the landing-gear spacing. Also shown in the figure is the geometric trail on the nose gear. Unlike the nose gear of the F-106, the nose gear of the Space Shuttle orbiter is corotating. (Both wheels must rotate at the same speed because they are physically splined to the same axle.) The nose gear doors were removed so they would not interfere with the tow cables or straps, and nose gear steering was disconnected to allow the nose gear to swivel freely.

Towing Techniques and Procedures

One of the techniques for towing an aircraft with a tricycle landing gear to measure side forces on the nose gear is shown in figure 6. The tow tug was connected by cables to a mooring lug on the nose gear of the aircraft and to the idler tug. The idler tug was unpowered so that the two tugs moved at the same speed. A third cable with a load cell in the line was connected between the idler tug and the nose gear of the aircraft and completed the right triangle cable arrangement. The length of the cables shown in figure 6 is not critical, but cables substantially shorter than those shown could make it more difficult for the tug drivers to track the desired ground path. Since there was no pilot in the airplane, a braking tug was attached by a bridle arrangement to the mooring lugs on the main landing gear for use in stopping the aircraft if it became necessary. The cable lengths were chosen to place the towing and idler tugs on expansion joints in the concrete so that the drivers could follow the joints and track parallel paths without moving the aircraft to the right or left. Figure 7 is a photograph of the first towing technique showing the aircraft, the tow tug, the idler tug, and the braking tug. A portable generator was attached to the idler tug to supply power to recording equipment mounted on the idler tug. Other photographs of the setup are shown in figures 8 through 12. Figure 8 shows the bridle arrangement attaching the braking tug to the aircraft main gear. The cable shown taut in the figure was allowed to slide loosely along the ground during towing to avoid undesired forces. A lightweight cord was attached to the left main gear for use as a guide for the braking tug operator to keep slack in the braking cable without overrunning the cable. A photograph of the rear of the towing tug is shown in figure 9. The two cables leaving the towing tug lead to the nose gear of the aircraft and the front of the idler tug. A photograph of the idler tug is shown in figure 10. The towing cable from the tow tug, the side-force cable to the nose gear, and the cable to one main gear of the aircraft are identified. Strain gauge tension links were installed in the cables to the aircraft to measure loads. Signals from these tension links were recorded on instrumentation mounted beside the tug operator. The cable shown in figure 10 leading to the main gear of the aircraft was used only for certain towing techniques and was not used for the technique shown in figure 6. A small piece of steel shown clamped to the side of the tug behind the front wheel was used as a guide for the tug operator to align the idler tug with the expansion joint so that the tug would track a straight line. A similar guide was used on the towing tug. The braking cable attachment to the braking tug is shown in figure 11. A bungee cord was used to limit the shock load in the braking cable to the main gear of the aircraft. If the bungee cord stretched 100 percent, a short length of cable would become taut and assume the remaining load. Figure 12 shows the nose gear of the aircraft with the towing cable attached by a shackle and the side-force cable to the idler tug attached by a strap to the yoke. The steering linkage was disconnected so that the nose gear was free to swivel.

Three tow configurations (shown in fig. 13) were investigated. Configuration A was the same as the configuration shown in figure 6. Configuration B was the same as configuration A, except that a cable was added from the idler tug to the right main gear of the aircraft. This configuration was tested to demonstrate a setup for measuring ply steer forces in the main gear. Another, perhaps simpler, configuration for measuring side forces on the nose gear was towing configuration C in figure 13. In this configuration, the towing tug was removed, and the idler tug was used to tow the aircraft through the cable from the right main gear. Although this scheme was simpler than the other two tow configurations, much greater side loads were introduced to the main gear.

Results and Discussion

Data are presented in tables I and II. For the F-106 test, data from tow configurations A, B, and C are included in table I as well as data for variations in left and right nose tire pressures. A typical side-force time history for run no. 3 is shown in figure 14. There were oscillations in the side-force trace, and a fairing of the data was used to obtain the average side force of 425 lb for the bank angle of 3°. In general, the initial and ending spikes in the side-force trace were ignored in the fairing to minimize the transients that occurred during starting and stopping. The F-106 was towed approximately 200 ft to obtain enough data to give a good fairing of the force trace. The side-force data listed in table I were obtained from fairings similar to that shown in figure 14.

Side-force data from tow tests of the Shuttle orbiter OV-101 are presented in table II. All the orbiter tow tests were conducted with tow configuration A for a nose tire pressure of 300 psi in both tires. A typical time history of side force for the Shuttle orbiter towed at a bank angle of 1° is shown in figure 15. A fairing of the data was again used to obtain the average side force of 1800 lb.

For both the F-106 and the Shuttle orbiter, the side force divided by the normal force of the nose gears gives the cornering-force coefficient, μ_c, listed in tables I and II and plotted in figure 16. Some of the scatter in the circular data points for the Shuttle orbiter may be caused by slight wind effects and small runway crown effects or a tow distance insufficient to permit a good fairing of the side-force data. Winds were slight, and crown effects were small; therefore, no attempt was made to normalize these factors. The dashed line, which is a fairing of the circular data points, has a slope of $0.06\mu_c$ per degree.

The square symbols in figure 16 are the cornering-force coefficients for the F-106 aircraft for bank angles up to 3°. The solid line is a fairing of the data forced through zero. The solid line fairing has a slope of $0.026\mu_c$ per degree. The F-106 data presented are only for nose tire pressures of 150 psi.

The data for both aircraft are shown together in figure 16 for convenience only, since the tire pressures, normal loadings, geometric trails, and tire sizes were quite different. In spite of the fact that the aircraft are quite different, it was felt that the effect of corotation was the major cause for the different slopes of the two straight-line fairings. The F-106 had independently rotating nose wheels, and the orbiter had corotating nose wheels. Additional data from tests subsequent to those of this report were published in reference 2 and indicate that corotation of nose wheels causes much higher side forces than independently rotating nose wheels.

Concluding Remarks

These tests have shown that an aircraft with a free-swiveling nose gear can still experience substantial side forces if it is rolling on a runway in a banked attitude due, for example, to a blown tire or deflated strut. A method of towing an aircraft to measure the side force due to bank angle has been demonstrated. Corotating nose wheels appear to cause a substantial increase in side force due to bank angle compared with independently rotating nose wheels.

NASA Langley Research Center
Hampton, VA 23665-5225
May 6, 1986

References

1. Stubbs, Sandy M.: *Landing Characteristics of a Dynamic Model of the HL-10 Manned Lifting Entry Vehicle.* NASA TN D-3570, 1966.
2. Daugherty, Robert H.; and Stubbs, Sandy M.: *A Study of the Cornering Forces Generated by Aircraft Tires on a Tilted, Free-Swiveling Nose Gear.* NASA TP-2481, 1985.

TABLE I. - TEST CONDITIONS AND SIDE-FORCE DATA FOR F-106 AIRCRAFT

[Normal load on nose gear = 4600 lb]

Run no.	Configuration	Bank angle, deg	Nose tire inflation pressure, psi		Side force, lb	μ_c
			Left	Right		
1	A	1	150	150	0	0
2	A	2	150	150	244	.05
3	A	3	150	150	425	.09
4	B	3	150	150	443	.10
5	C	3	150	150	457	.10
6	A	3	75	150	322	.07
7	A	3	150	75	389	.08

TABLE II. - TEST CONDITIONS AND SIDE-FORCE DATA FOR SHUTTLE ORBITER OV-101

[Normal load on nose gear = 21 474 lb; nose tire inflation pressure = 300 psi; tow configuration A]

Run no.	Bank angle, deg	Side force, lb	μ_c
1	0	600	0.03
2	.02	225	.01
3	.41	350	.02
4	.44	1100	.05
5	1.03	1100	.05
6	1.04	1275	.06
7	1.05	1950	.09
8	1.05	1750	.08
9	1.07	1350	.06
10	1.66	1600	.07
11	1.77	1600	.07
12	2.07	2850	.13
13	2.28	2900	.14
14	2.33	2600	.12
15	2.33	2850	.13

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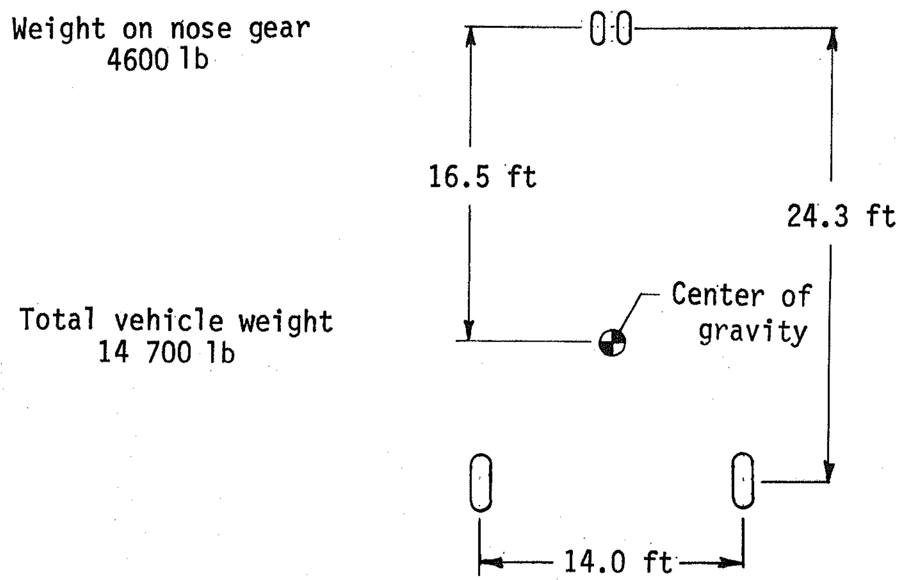
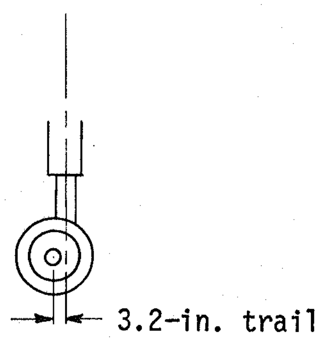
Figure 1. F-106 aircraft.



(a) Landing-gear spacing.



(b) Trail on nose gear.

Figure 2. Landing-gear spacing and nose gear trail for F-106 aircraft.

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Figure 3. Differential strut strokes to produce bank angle of 3°.

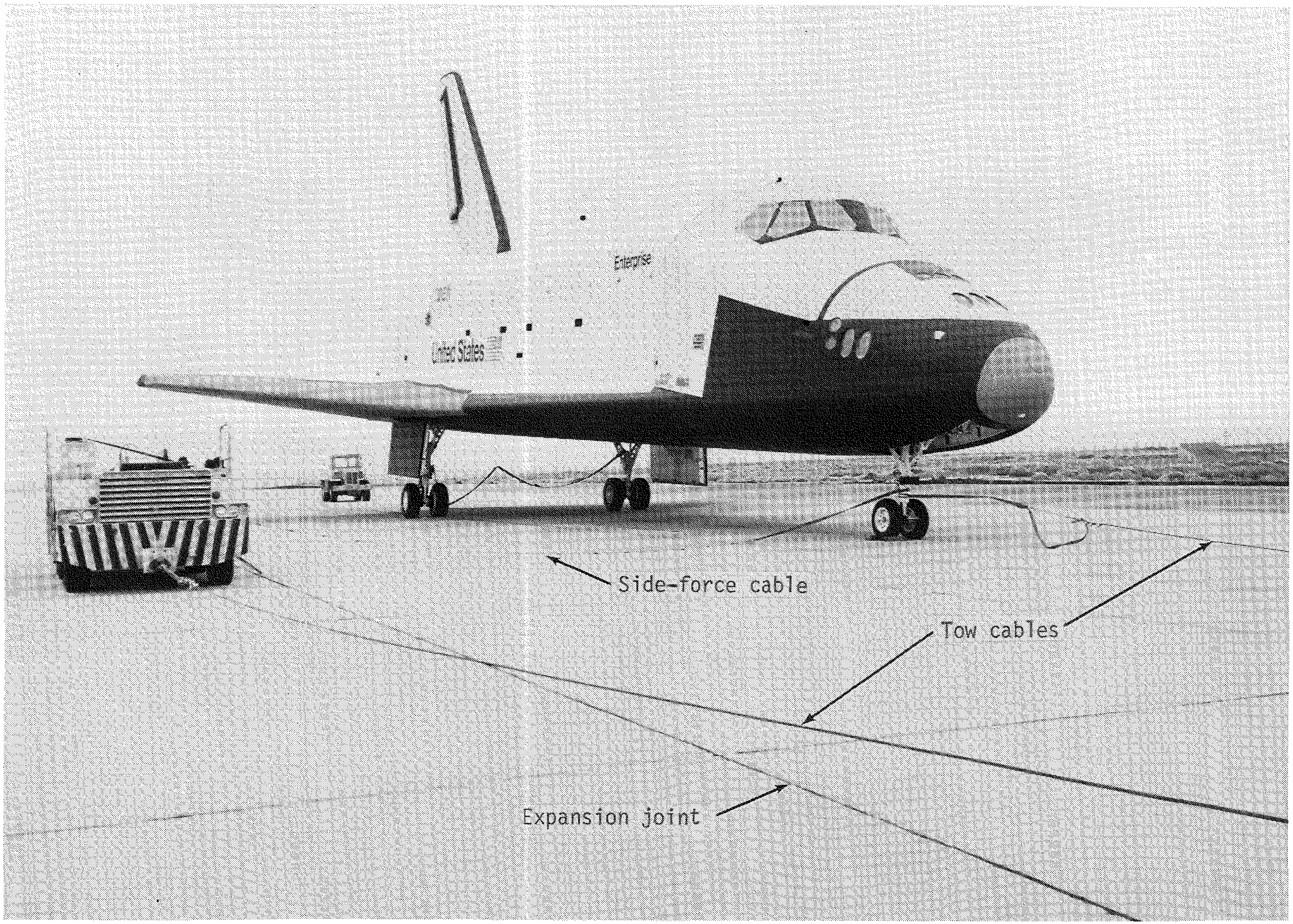

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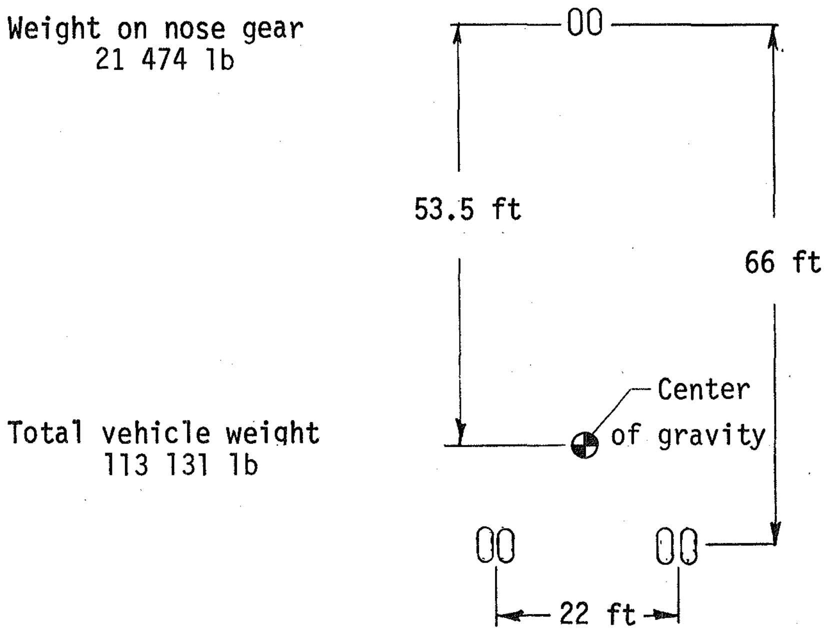
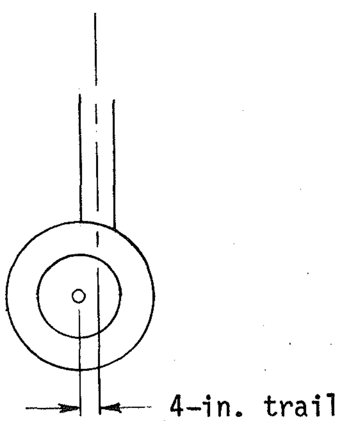
Figure 4. Shuttle orbiter OV-101.



(a) Landing-gear spacing.



(b) Trail on nose gear.

Figure 5. Landing-gear spacing and nose gear trail for Shuttle orbiter OV-101.

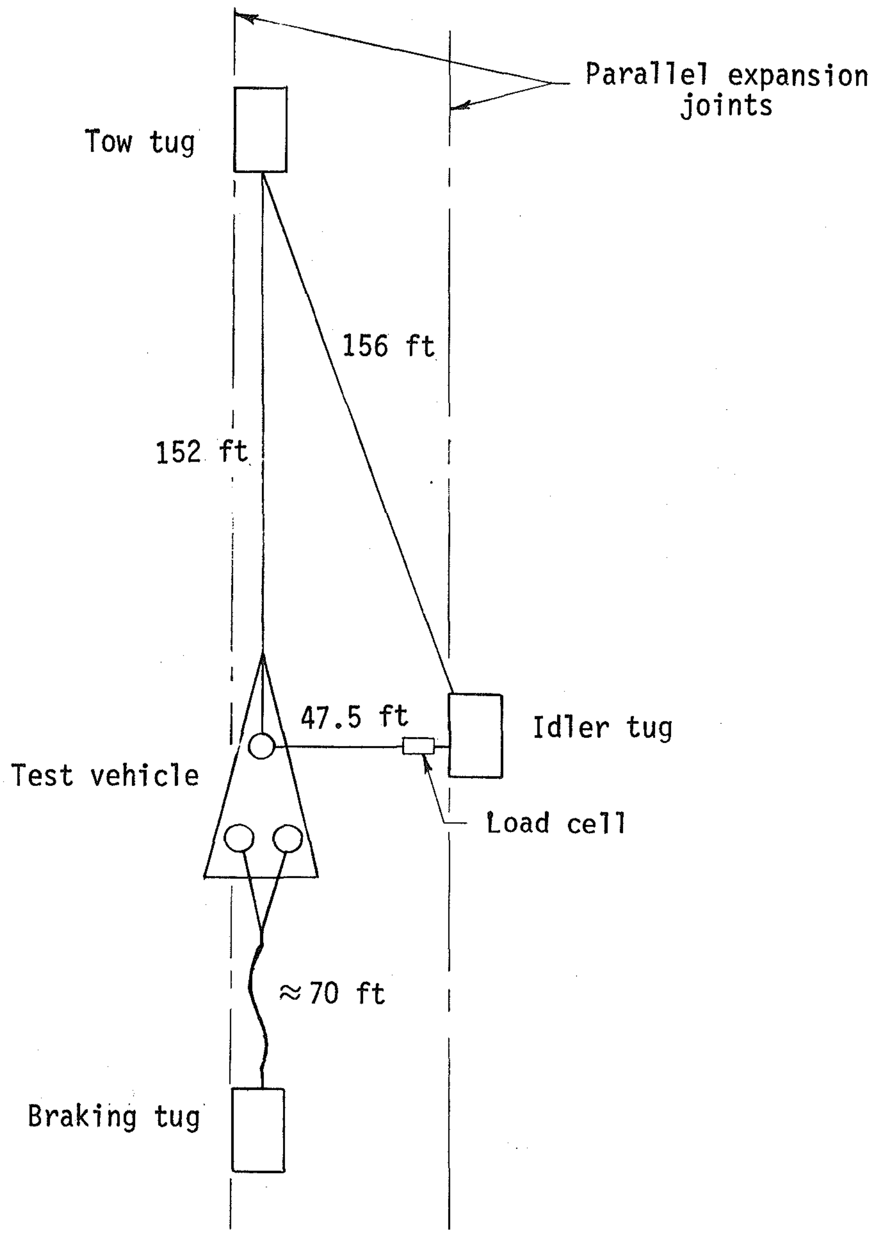


Figure 6. Setup of one towing technique.

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Figure 7. F-106 tow test setup.

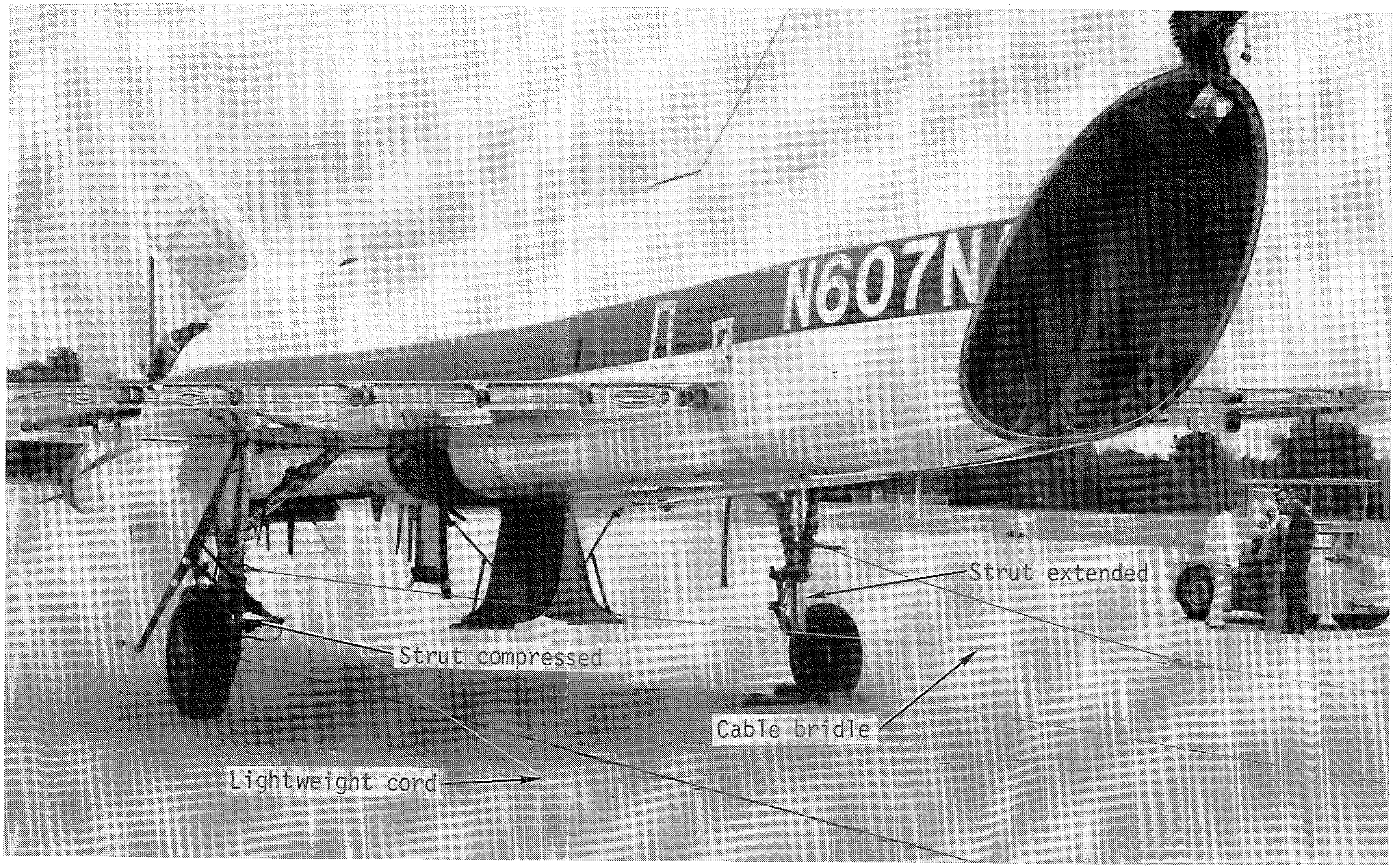

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Figure 8. Cable bridle for braking tug.

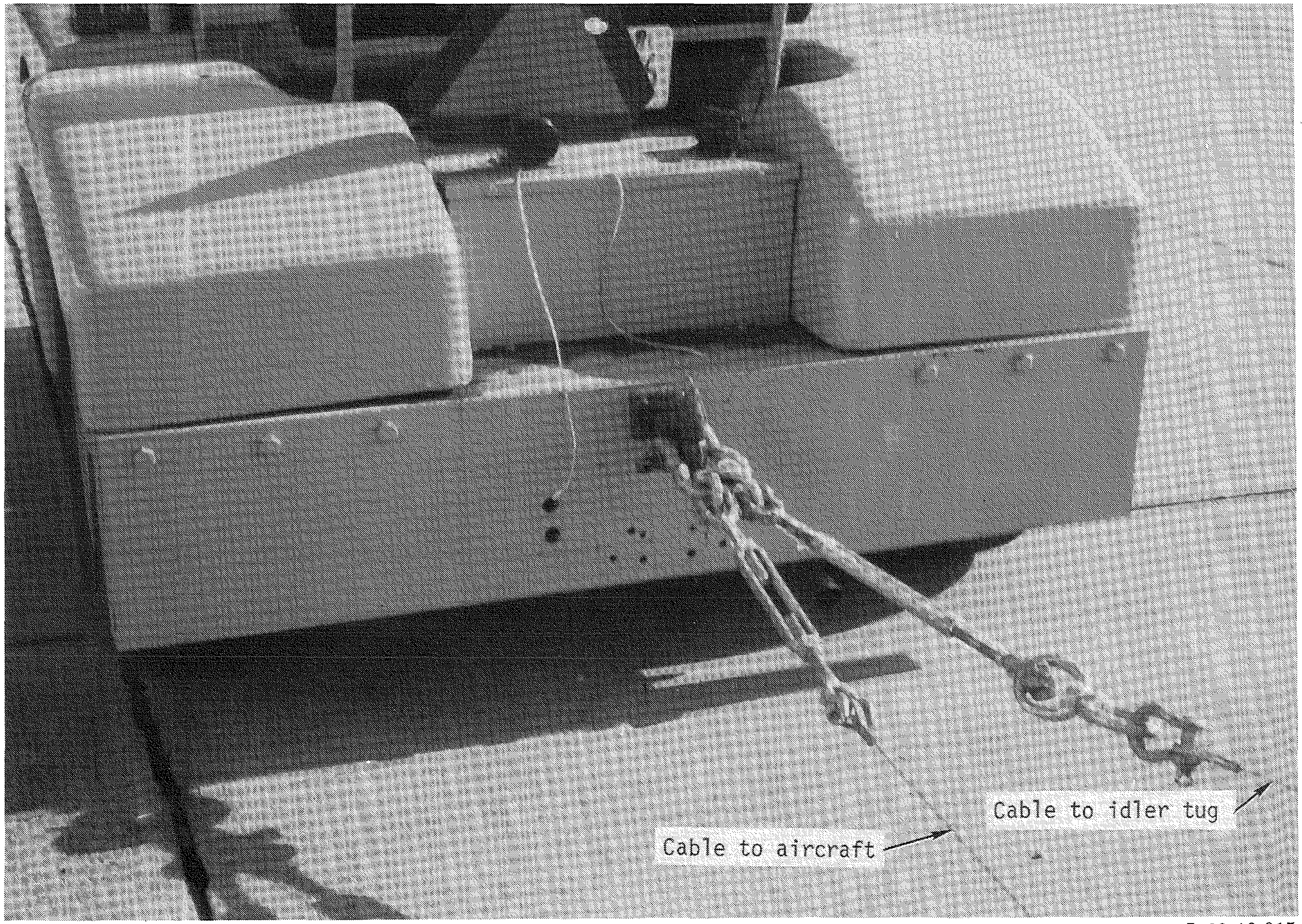

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Figure 9. Towing tug with tow cables attached.

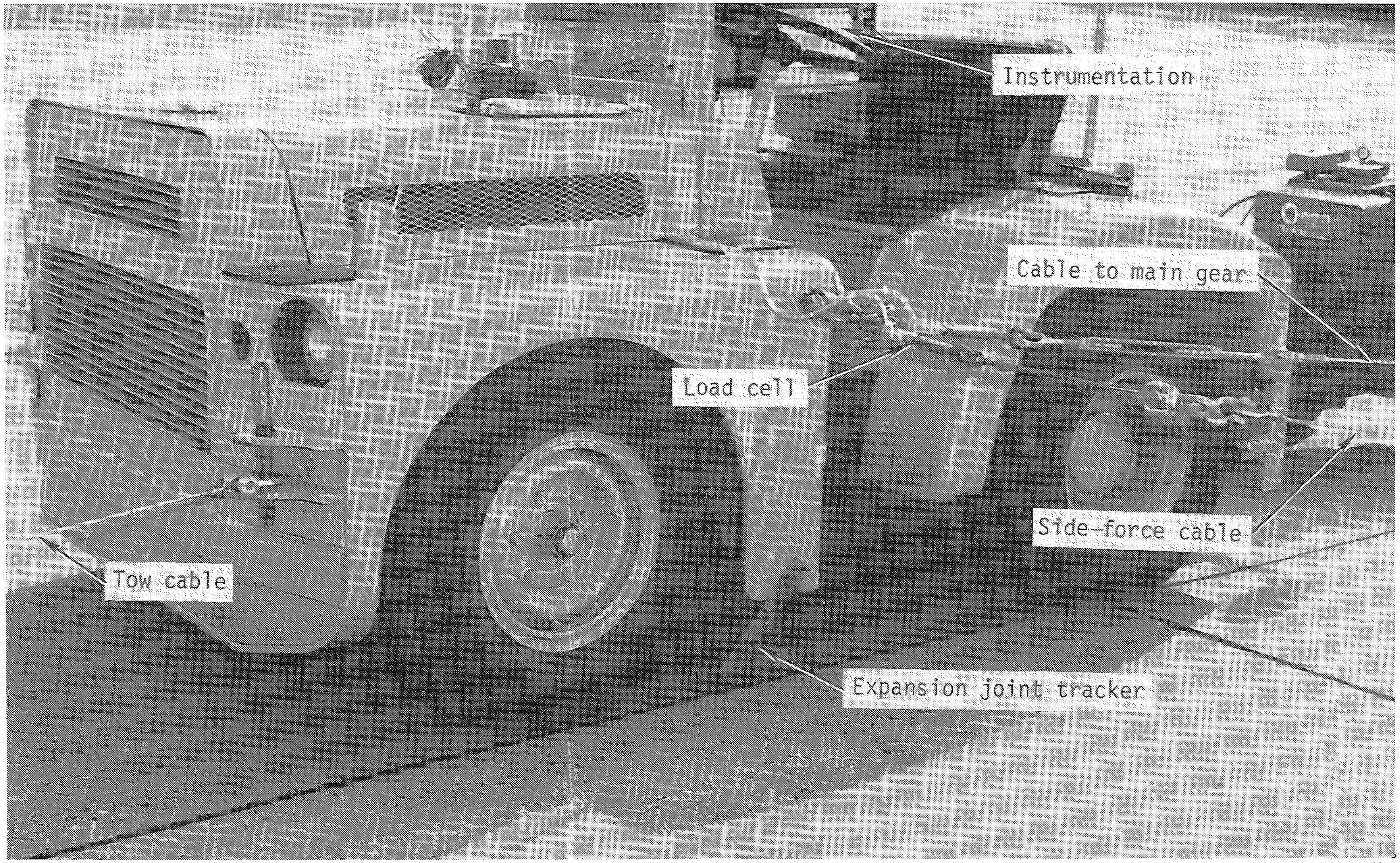

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Figure 10. Idler tug with instrumentation.

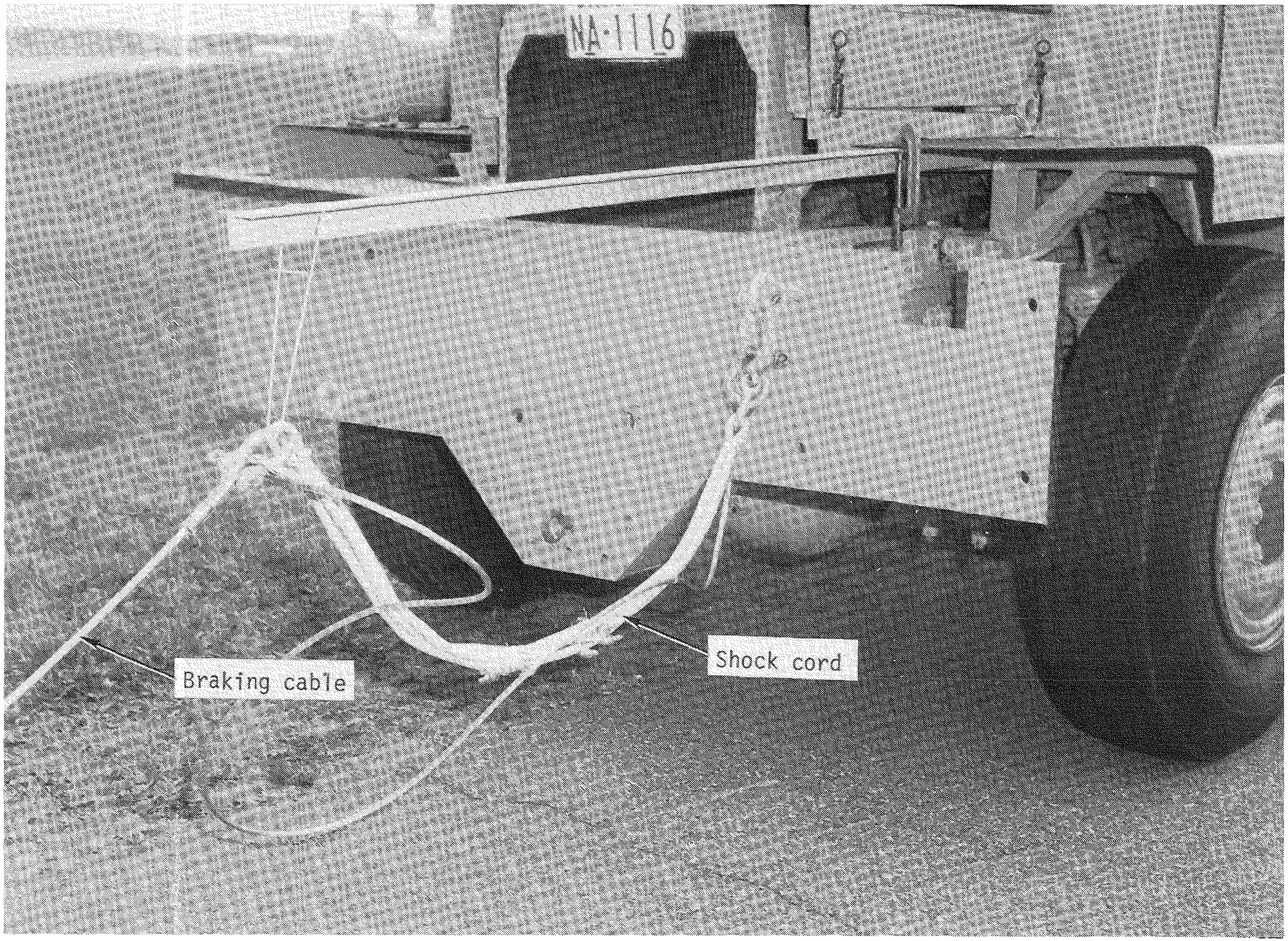

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Figure 11. Braking tug.

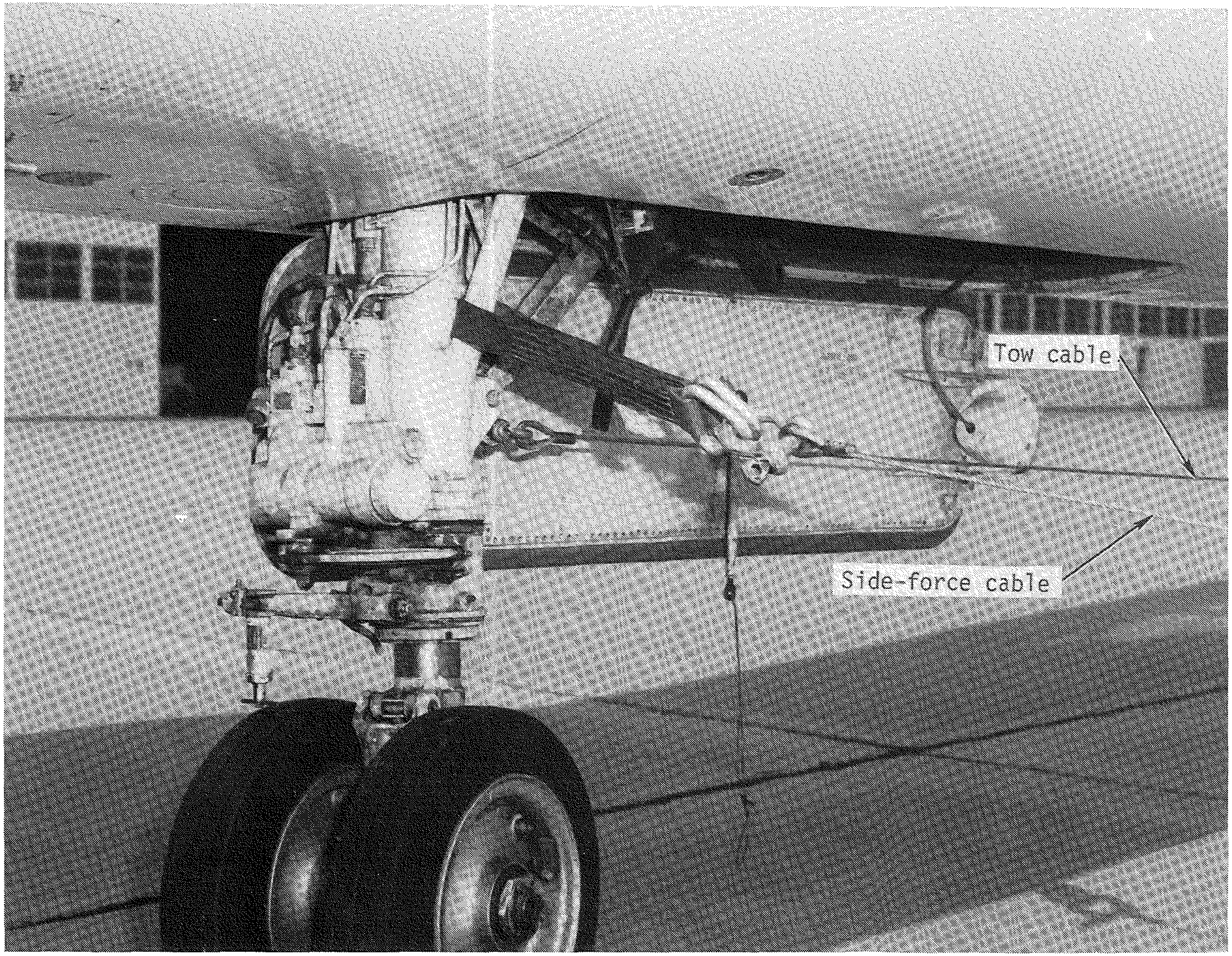

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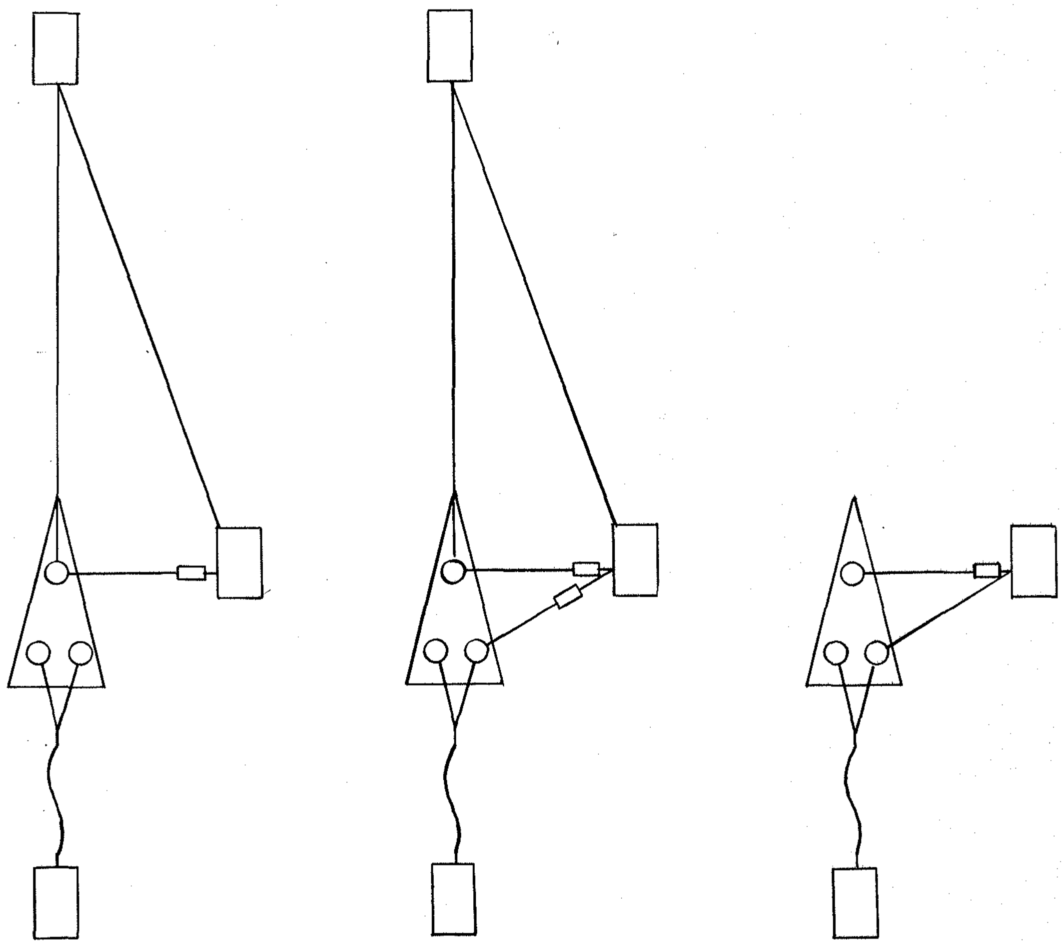
Figure 12. F-106 nose gear and cable connections.



Configuration A Configuration B Configuration C

Figure 13. Towing techniques evaluated.

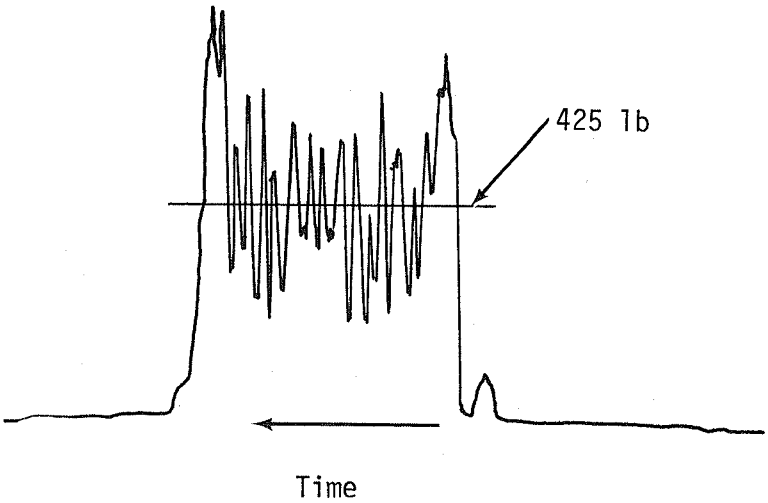


Figure 14. Typical side-force time history for F-106. Towing configuration A at bank angle of 3°.

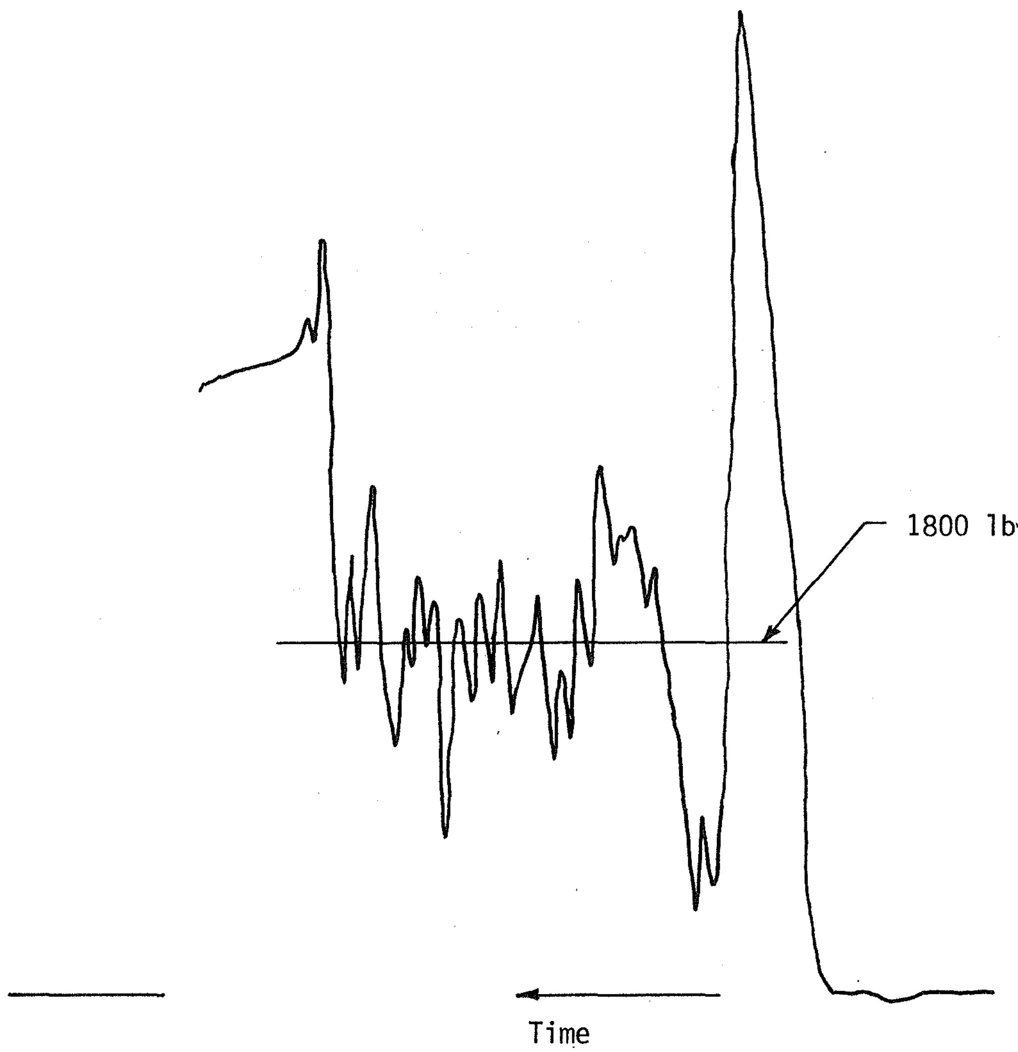


Figure 15. Typical side-force time history for Shuttle orbiter OV-101 at bank angle of 1°.

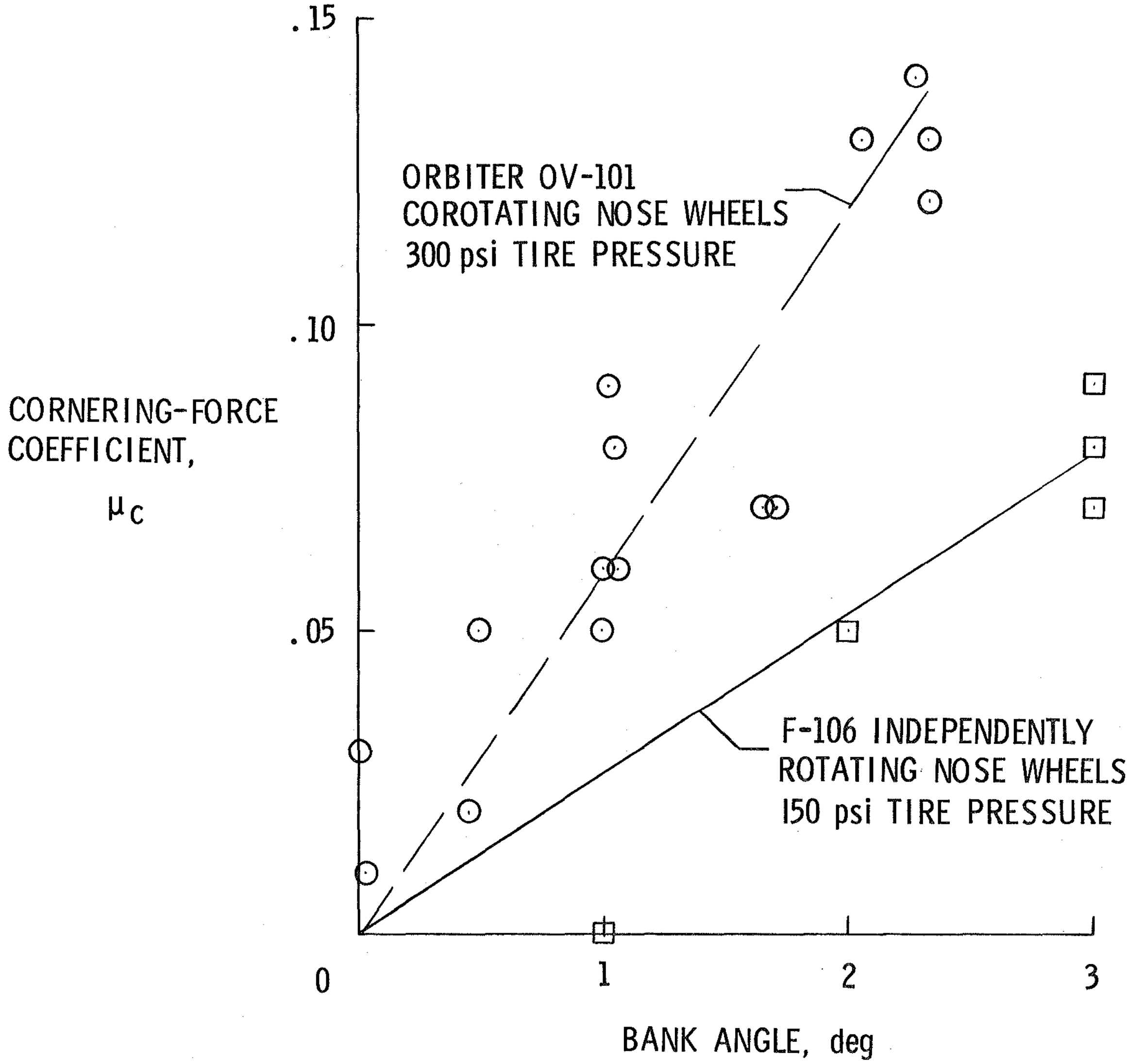


Figure 16. Cornering-force coefficients for both Shuttle orbiter OV-101 and F-106 for bank angles up to 3°.

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15. Supplementary Notes

16. Abstract

An experimental investigation was conducted at the Langley Research Center to determine a method for towing an aircraft to measure the side forces of a free-swiveling nose gear due to variations in bank angle. An F-106 aircraft and the Space Shuttle orbiter OV-101 were towed to measure side forces on full-size aircraft for bank angles up to 3°. These tests indicate that substantial side forces will occur if an aircraft is rolling on a runway in a banked attitude even when the nose gear is free to swivel. Corotation of a twin-tire nose gear appears to cause a substantial increase in side force due to bank angle compared with a nose gear with independently rotating wheels.

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