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AN INVESTIGATION OF THE INCREASE IN VORTEX INDUCED ROLLING MOMENT ASSOCIATED WITH LANDING GEAR WAKE

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Tests in the Langley Vortex Research Facility indicate that the wake produced by the landing gear may possibly form an aerodynamic endplate or reflection plane at the inboard edge of each inboard flap which increases the effective aspect ratio of the flap and thereby increases the strength of the flap outer edge vortex.

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Langley Research Center

SUMMARY

As part of a NASA-wide program now underway to attempt to reduce the hazard associated with the lift-induced vortex system of large aircraft, a flight test has been conducted at Flight Research Center to verify the results found in the ground base facilities of the effect of span lift load variation as well as the vortex attenuation of the high energy jet engine exhaust through proper thrust programming. During these flight tests a large increase in vortex strength was experienced as a result of extending the landing gear.

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INTRODUCTION

The introduction of the large wide-body jet transport aircraft into airline service has created an air traffic hazard which requires a large separation distance between aircraft, reducing the air-terminal utilization by a factor of possibly four, as a result of the strength and persistent nature of the lift-induced wing-tip vortex. An accelerated research effort is now underway throughout the NASA in an attempt to significantly reduce or possibly eliminate the wake vortex system produced by a passing aircraft. Ideally any such fix would be retrofitted to existing aircraft to cope with the vortex persistence problem.

Flight tests were conducted at the Flight Research Center to determine the full scale effect of several such fixes which had shown promise in ground facilities as a means of vortex alleviation. During these tests an unexpected increase in vortex strength was experienced as a result of extending the landing gear. An investigation has been conducted in the Langley Vortex Research Facility to determine the mechanism associated with the landing gear wake and the strength of the shed vortex systems of the Boeing 747. The results of this investigation are reported here along with the effects of span load variation and engine thrust on vortex attenuation.

APPARATUS AND PROCEDURES

Test Facility

An overall internal view of the Langley Vortex Research Facility is shown in figure 1. A carriage is shown mounted on the 1800-foot overhead track with a 0.03-scale model of the 747 blade mounted beneath the carriage. A following model is located at 160 feet downstream of the vortex generating model (a scale distance of 1 mile) through a series of trailers to measure the rolling moment induced by the vortex of the lead model.

The test section, constructed to isolate the wake of the carriage and trailers from the model wake, is 300 feet long with a 2-inch opening along the center of the ceiling to allow the model blade mounts to pass. The exterior of the building shown at the entrance of the test section encloses the entire length of the track.

The overhead track extends a thousand feet upstream of the entrance to the covered area where each test is initiated. After the carriage is launched, the automotive drive system accelerates through first and second gear to a velocity of 100 feet per second which is held constant by a cruise control throughout the length of the covered area. One hundred feet inside the covered area is considered the test position where smoke (vaporized kerosene) is deployed for flow visualization. (See ref. 1.) At this point, high-speed cameras are used to film the motion of the vortex produced by the generating model while the aerodynamic forces experienced by the model are recorded. One and six-tenths of a second later the following model reaches this test point measuring the vortex induced roll. The position of this model relative to the vortex core may be determined visually while the induced rolling moment is recorded. Caliper brakes are applied as the vehicle leaves the covered area bringing the vehicle to a 1 "g" stop over the next 250 feet of track.

Model

The vortex-generating model is a 0.03-scale model of the Boeing 747 transport aircraft. This model is blade mounted on an internal six-component strain-gage balance beneath the drive vehicle. High-pressure air is piped from a bottle field onboard the vehicle down the rear portion of the model blade mount to each engine nacelle for thrust simulations. The thrust of each engine is individually controlled to allow a difference in thrust level between the outboard and inboard engines. The model is equipped with both leading and trailing-edge flaps to simulate the landing as well as the cruise configuration.

The following model used to measure the roll induced by the vortex of the lead model is a DC-9 class transport. The vertical and lateral position of the following model may be varied to fix this model in the vortex generated by the lead model. This position of the roll model relative to the vortex is recorded by a television camera which allows an instant replay of each test to determine the degree of vortex core penetration. A one component internal strain-gage roll balance is used with this model.

DISCUSSION OF RESULTS

Full-flap configuration.- The vortex induced rolling moment coefficient measured in the Vortex Research Facility at a scale distance of 1 mile behind the Boeing 747 vortex generating model at a lift coefficient of 1.2 is presented in figure 2 for various flap arrangements and engine thrust levels. The induced rolling moment coefficient produced by the full-flap configuration shown as a base line in this figure is approximately 0.09 which represents the total energy of the vortex system of one wing panel including the combined strength of the wing tip vortex and the vortex created by full-flap system. The wing tip and flap vortex are shown visually in figure 3 as the model passes through the smoke screen. The wing tip vortex orbits very rapidly about the stronger flap vortex forming the classical vortex sheet between the two vortices. In this case the majority of the lift is produced over the flap span while only a small amount of lift is carried by the wing tip as indicated by the orbital movement of the tip vortex about the flap vortex.

The flight results presented in reference 2 indicate that with the Boeing 747 configured for landing (the inboard and outboard flap deployed at 30°, noted as flaps 30/30) the pilot judged an unsafe limit for the T-37 and Learjet was approached just under a separation distance of 9 miles with the 747 engines at idle thrust and approximately 7 miles at the engine thrust level required for level flight with full flap deployed.

Span lift load variation.- Retracting the outboard flaps of the model as a means of changing lift across the span of the wing results in a sizeable reduction in the vortex induced rolling moment (ref. 3). The strength of the vortex is approximately 45 percent of that resulting from the full-flap configuration (fig. 2). The visual model data of figure 4 indicate that there are two separate vortex systems produced by each wing panel, that created by the outer and inner edge of the inboard flap set at 30° and the wing tip vortex which should be stronger than the tip vortex of the full-flap configuration because the outer wing panel is now required to carry more lift to maintain the same lift coefficient. The measured strength of the wing tip vortex is approximately equal to that of the flap. (See fig. 2). The model visual data also indicate that the vortex created by the inner edge of each inboard flap is completely dissipated by the time 3/4 miles (frame 12) is reached. This is a result of the presence of the fuselage and the influence of each inner edge vortex on the other due to their proximity and opposite sense of rotation which in this unique case is counter to the wing-tip vortex and opposes the aircraft downwash. The flap outer edge vortex still exists at this point and is responsible for the rolling moment results measured and presented as the second configuration in figure 2. The wing tip vortex has orbited approximately 270° and is near the plane of symmetry at a vertical position well below the flap outer edge vortex at the 3/4-mile position. (See fig. 4, frame 12).

The flight results obtained with the outboard flaps retracted (30/0 configuration) resulted in a required separation of approximately 5-1/2 miles at idle thrust and approximately 3 miles at the high thrust levels required for level flight indicating the attenuating effect of engine thrust (ref. 2).

Effect of landing gear.- Extending the landing gear during the flight test resulted in an unexpected increase in the vortex induced rolling moment, requiring an increase in separation distance between the generating and chase aircraft from approximately 3 miles to 6 miles. It was generally assumed that the effect of the landing gear would be favorable such that the turbulent wake of the gear would tend to reduce the strength of the already weakened inboard flap inner edge vortex reducing the strength of the overall vortex system of the 30/0 flap configuration. An analysis of the visual data obtained during the flight test as the gear was extended indicated that a very strong wake is produced by the landing gear which may very possibly form an aerodynamic endplate or reflection plane on the inner edge of the inboard flap. If this is the case, the endplate effect of the gear wake would prevent the movement of the stream flow around the inner edge of the inboard flap as normal and force this flow to move to the outer edge of the flap. This action would increase the effective aspect ratio of this flap as a result of the now quasi-semispan flap configuration and thereby increase the strength of the vortex created at the flap outer edge which now encompasses the entire vortex energy associated with this flap. The model force test results obtained from the 30/0 flap configuration with the landing gear extended (fig. 2) also indicate this same increase in vortex induced rolling moment experienced during the flight test. (Also see fig. 5.)

The model visual data of the 30/0 flap configuration with gear extended, presented in figure 5, indicate a more distinct vortex formation at the flap outer edge as the model passes through the smoke screen. This would indicate an increase in strength of this vortex at the moment it is created rather than through the interaction of the multi-vortex system at some downstream position. The wing tip vortices appear to be more clearly defined indicating that the gear-endplate effect may even extend to the wing tip.

Effect of flap endplates.- In an attempt to verify the theory that the wake generated by the landing gear aerodynamically changed the aspect ratio of the flap, a physical endplate was fixed to the inner edge of each inboard flap which was approximately 2 mean chords in length and 1 mean chord in height. The rolling moment coefficient resulting from this model configuration (fig. 2) is similar to that resulting from extending the landing gear indicating that the landing gear wake is very possibly endplating the inboard flap as suspected. The visual data presented in figure 6 indicate that the flap inboard vortex is eliminated entirely while the vortex at the flap outer edge is visually strengthened. It is interesting to note that this vortex from the outer edge of the flap breaks down at approximately 1/2 mile (frame 8) behind the generating aircraft in an almost explosive fashion. This phenomenon has not been observed in early investigations and may, as an effect of the endplate, be the result of an increase in the vortex swirl velocity of such a magnitude compared to the vortex axial flow that the vortex becomes unstable and breaks down as shown in reference 4. The circulation which surrounds the vortex is still present and is the cause of the rolling moment measured by the following model.

Model tests are being performed at the Ames Research Center in an attempt to reduce the landing gear effect by removing the inner 30 percent of each inboard flap (tests incompleted). This would permit the flow between the two inboard flaps to return to normal even though the gear are extended. The vortex alleviating effect of this flap modification tends to support the theory that the gear wake is blocking the stream flow at the inner edge of the inboard flaps diverting the flow to the flap outer edge.

Unpublished results of more recent flight tests at the Flight Research Center of spoilers examined in the Langley V/STOL Tunnel indicate that the vortex attenuating effect derived from deploying the inboard two of the four spoilers located just forward of the outboard flap was reduced as a result of extending the landing gear. The required separation distance between the Boeing 747 and the T37 chase aircraft was doubled. The roll measured with the two outboard spoilers deployed was unaffected by extending the gear. The outboard spoiler position relative to the outboard flap-tip, where the strongest vortex is produced, is more favorable and dissipation of the flap outer edge vortex is greater as the data indicate. The absence of a landing gear effect indicates again that it is the outer flap edge vortex that is strengthened during the formation of the vortex by the landing gear endplate effect and is alleviated by the wake of the spoiler and the high energy wake of the outboard engines located at the flap outer edge.

<u>Fuselage flap</u>.- A fuselage flap was installed between the two inboard flaps in an attempt to further increase the swirl velocity of the inboard flap outer edge vortex and possibly excite an even earlier vortex breakdown. The fuselage flap was attached to the lower surface of the fuselage just behind the landing gear and extended down to the trailing edge of the inboard flaps. This configuration resulted in a similar increase in vortex swirl velocity and an abrupt dissipation found visually during flap endplate investigation. Oddly enough, the flap and wing tip vortex (fig. 7) form very rapidly into a single vortex in less than 3/4 miles (frame 12) behind the generating aircraft which is not the case for the 30/0 configuration. There is an increase

in the induced rolling moment associated with the fuselage flap configuration as expected compared to the inboard flap configuration with little or no effect from extending the landing gear. This roll increase is the result of the combined strength of the flap and wing tip vortex plus the increase in flap loading resulting from the addition of the fuselage flap lift.

Effect of thrust and fuselage flap.- An attempt was made to further alleviate the vortex induced rolling moment of the fuselage flap configuration by the addition of thrust. Operating the outboard engines of the 747 model at full thrust did result in a reduction in vortex roll (presented in fig. 2) due to the more rapid orbital rate of the flap and wing tip vortex of this configuration which positioned the wing-tip vortex in the line-of-thrust of the outboard engine. (See fig. 7.)

During landing the Boeing 747 requires approximately 25 percent of the total thrust of the four engines; therefore, by operating the two outboard engines at full thrust for vortex dissipation, there is a thrust surplus equal approximately to the maximum thrust of one engine. Part of this thrust overage is absorbed by a small 6.4 cm diameter flat plate disk probe mounted approximately 7.6 cm downstream of each wing tip, and is included in the final data shown on figure 2. This device also reduces the strength of the vortex created at the wing-tip as a result of the induced flow in the flight direction which possibly disrupts the vortex axial flow causing the vortex to break down. (See ref. 5.) Any additional drag that may be required may possibly be produced by operating the inboard engine thrust reversers at the level required to maintain a 3° glide slope.

CONCLUDING REMARKS

An investigation has been conducted in the Langley Vortex Research Facility to determine the mechanism behind the increase in vortex induced rolling moment associated with extending the landing gear of the Boeing 747 experienced during flight tests at the Flight Research Center. This investigation has shown that this increase in vortex strength is a result of the aerodynamic endplate effect of the landing gear wake on the inner edge of the inboard flaps which increases the effective aspect ratio of this flap and thereby increases the strength of the flap outer edge vortex. This gear endplate effect may be alleviated to some degree by removing the inner portion of the inboard flaps as tested by the Ames Research Center, or by deploying spoilers in the vicinity of the flap outer edge tested by the Langley V/STOL Tunnel and Flight Research Center.

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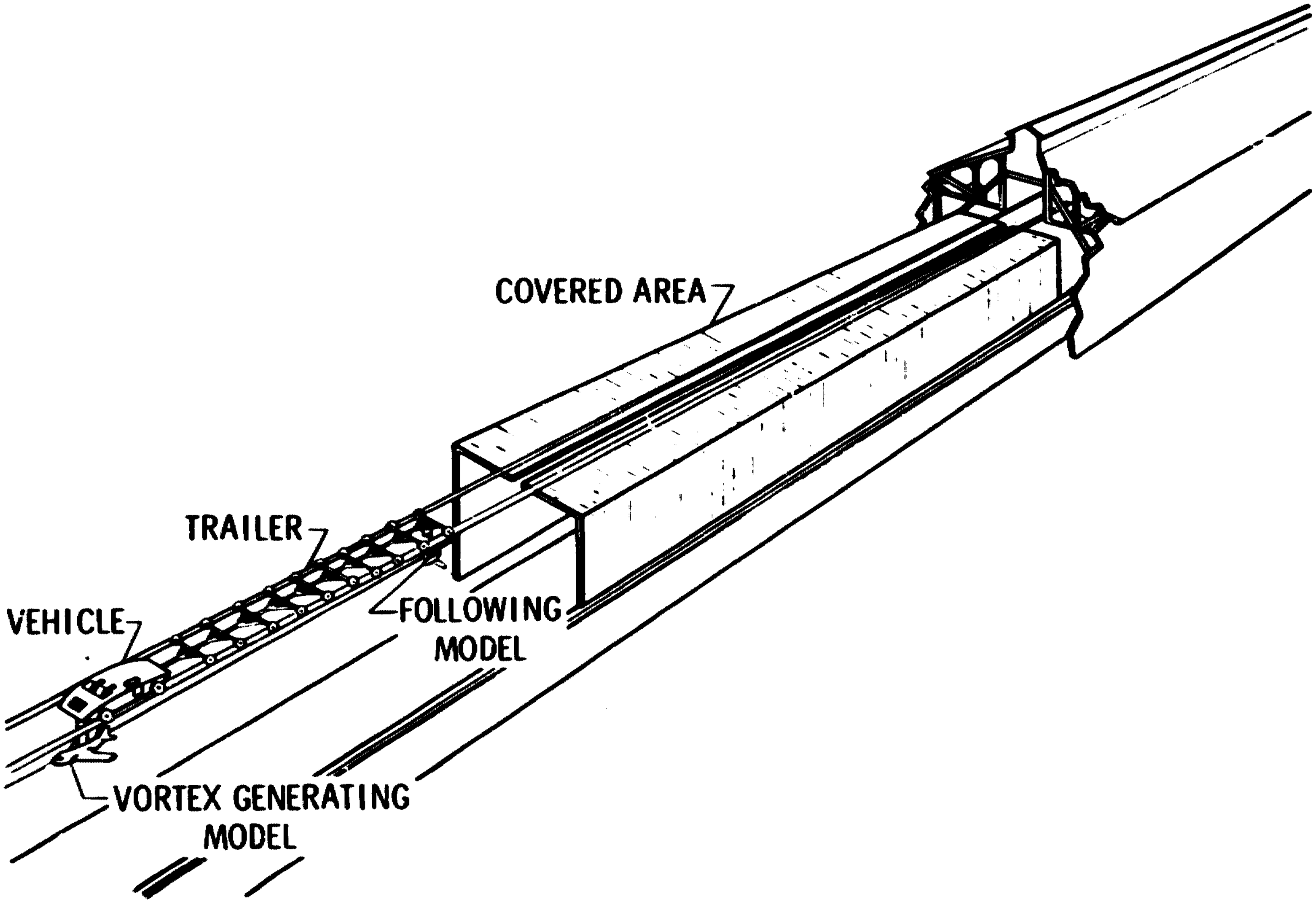

Figure 1.- The Langley Vortex Research Facility.

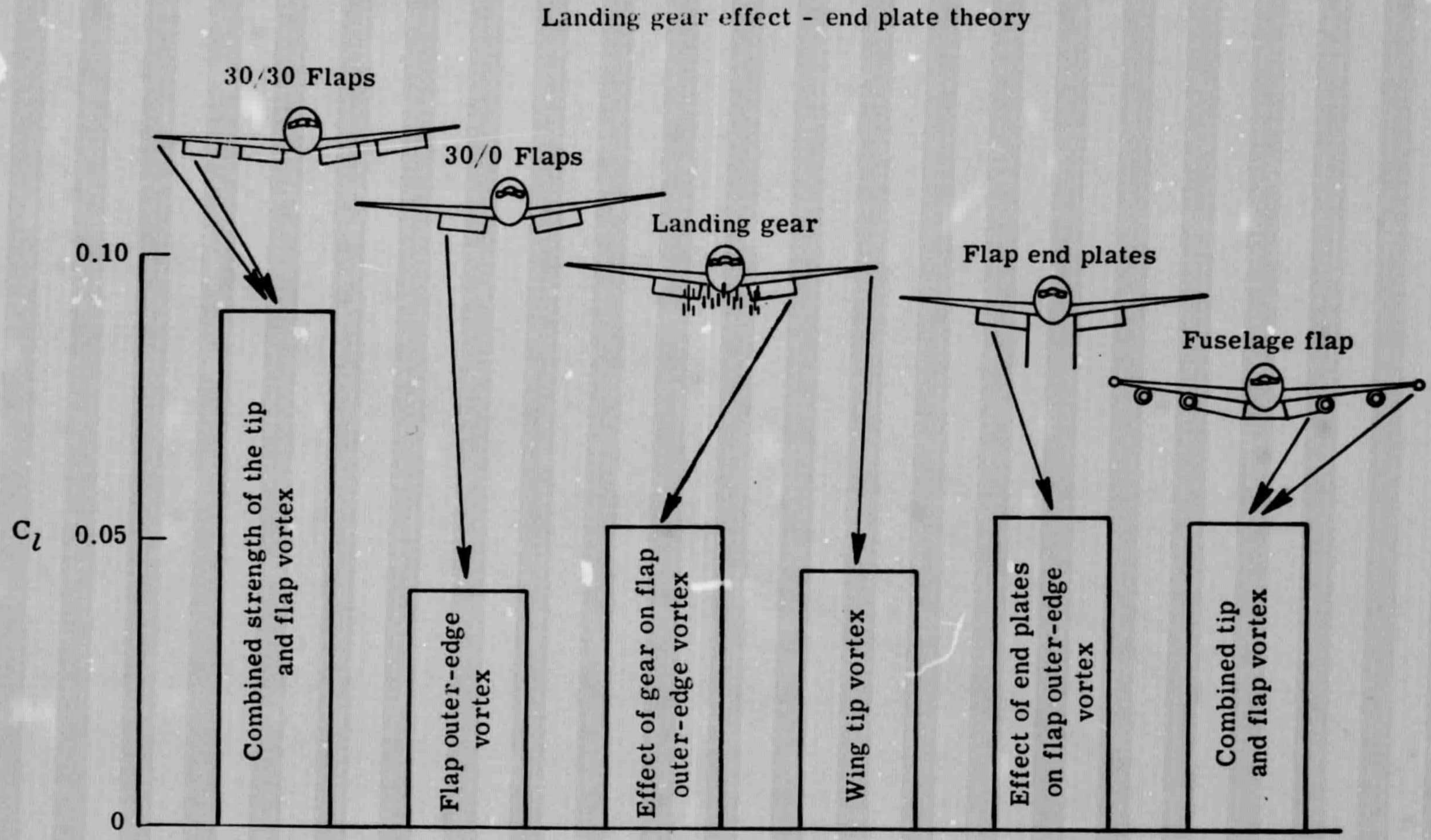

Figure 2. - Lift induced rolling moment of a 0.03-scale model of the Boeing 747 at a lift coefficient of 1.2 measured at a scale distance of one mile by a DC-9 class model.

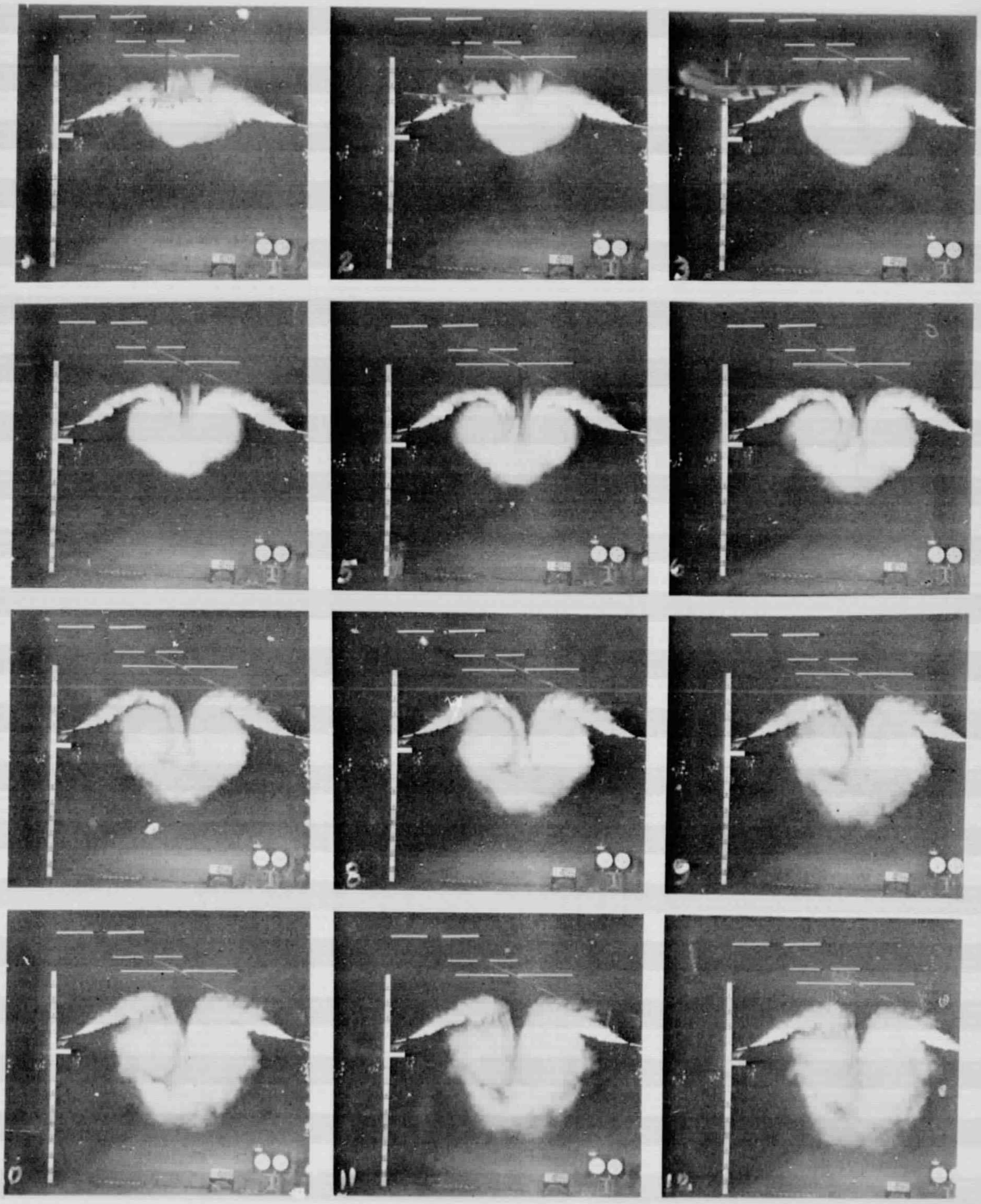

Figure 3. - A time history of the vortex system of the Boeing 747 at a lift coefficient of 1.2 with full flap deployed model velocity ≈ 30.5 m/second, camera speed = 10 frames/second.

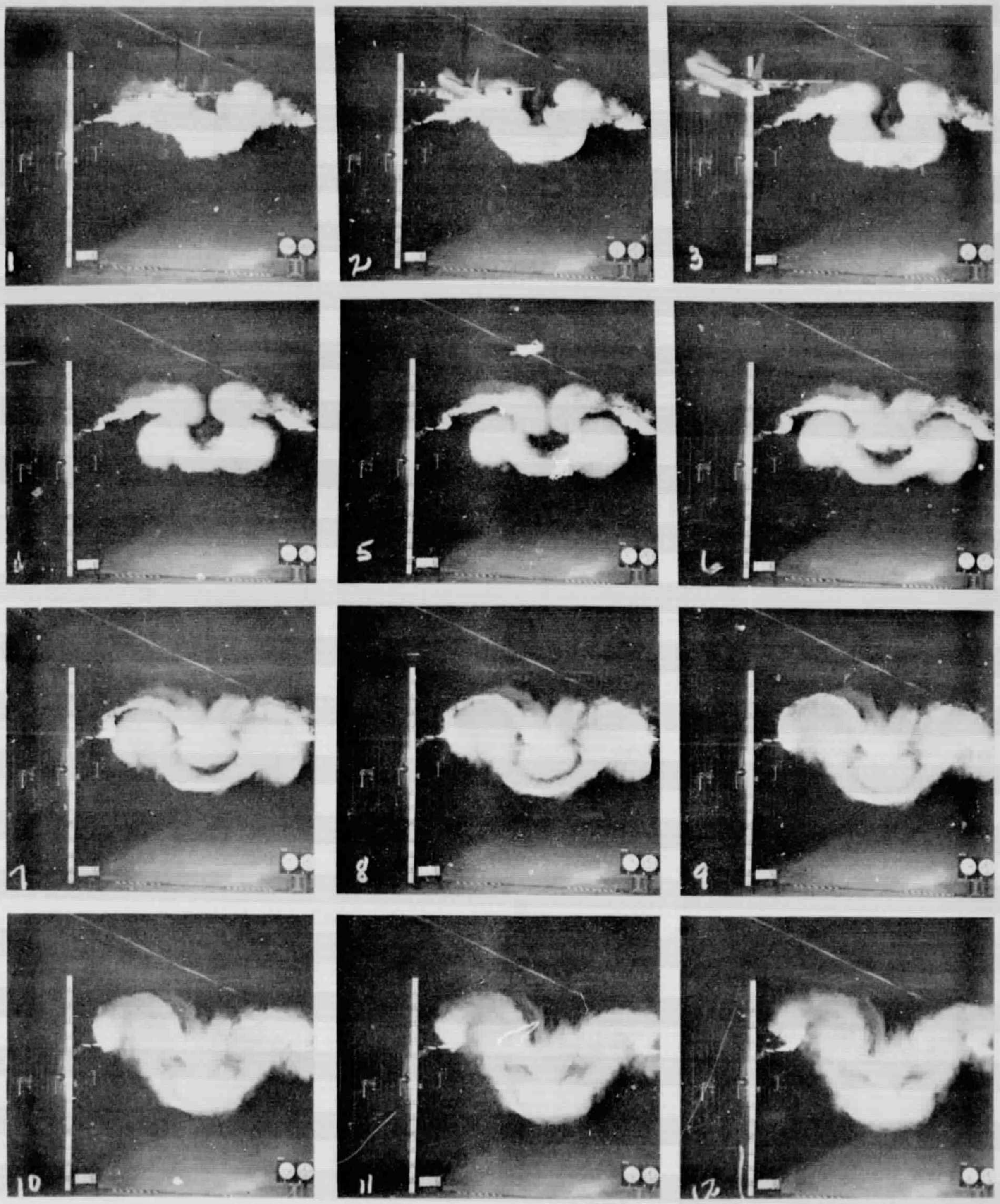

Figure 4. - Visual effect of a change in span lift load (outboard flap retracted, 30/0 configuration) on the development and decay of the vortex system of the Boeing 747 at a lift coefficient of 1.2. Model velocity ≈ 30.5 m/second, camera speed = 10 frames/second.

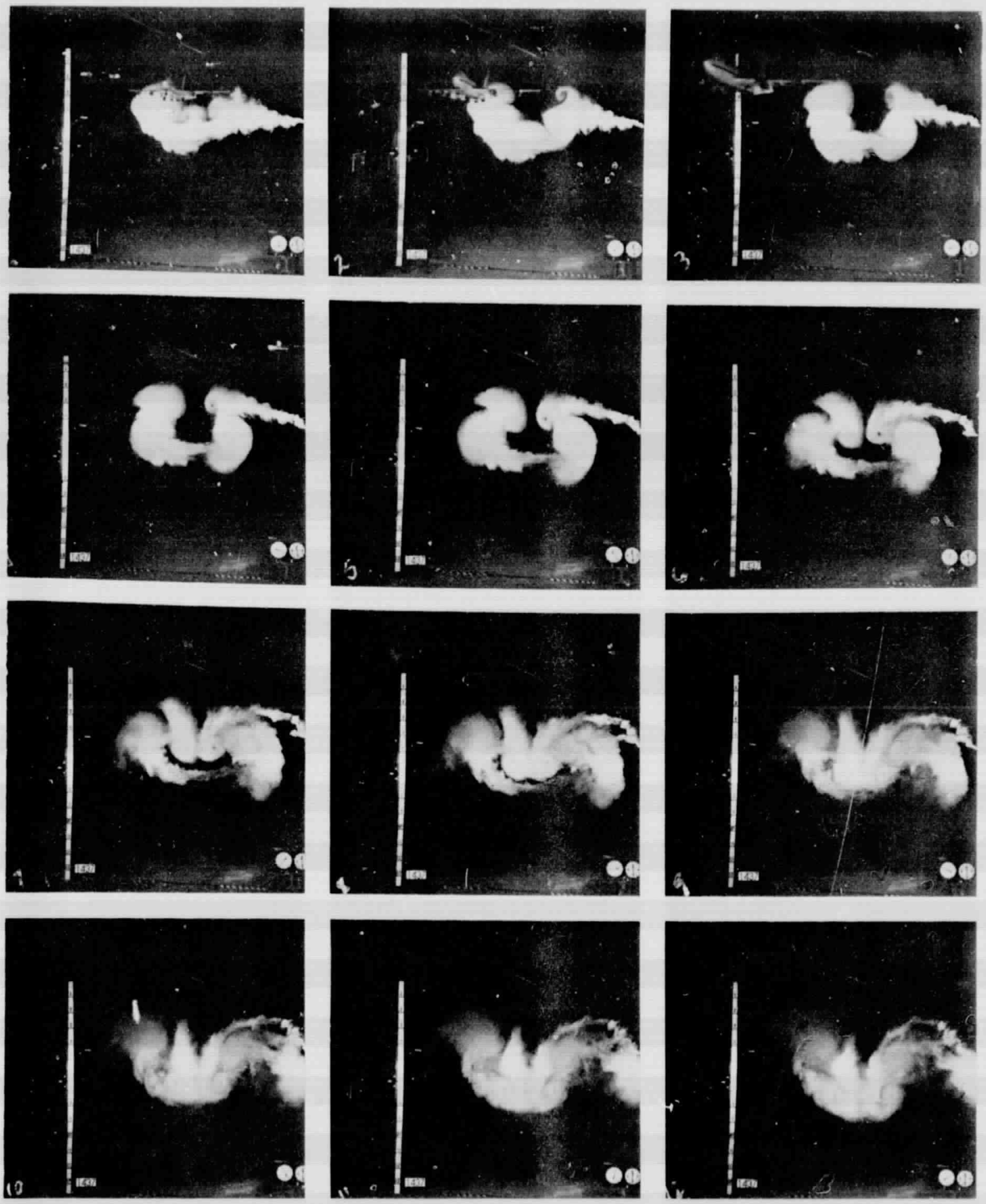

Figure 5. - Visual effect of landing gear on the vortex system of the 30/0 Boeing 747 landing configuration. Lift coefficient = 1.2, model velocity ≈ 30.5 m/second, camera speed = 10 frames/second.

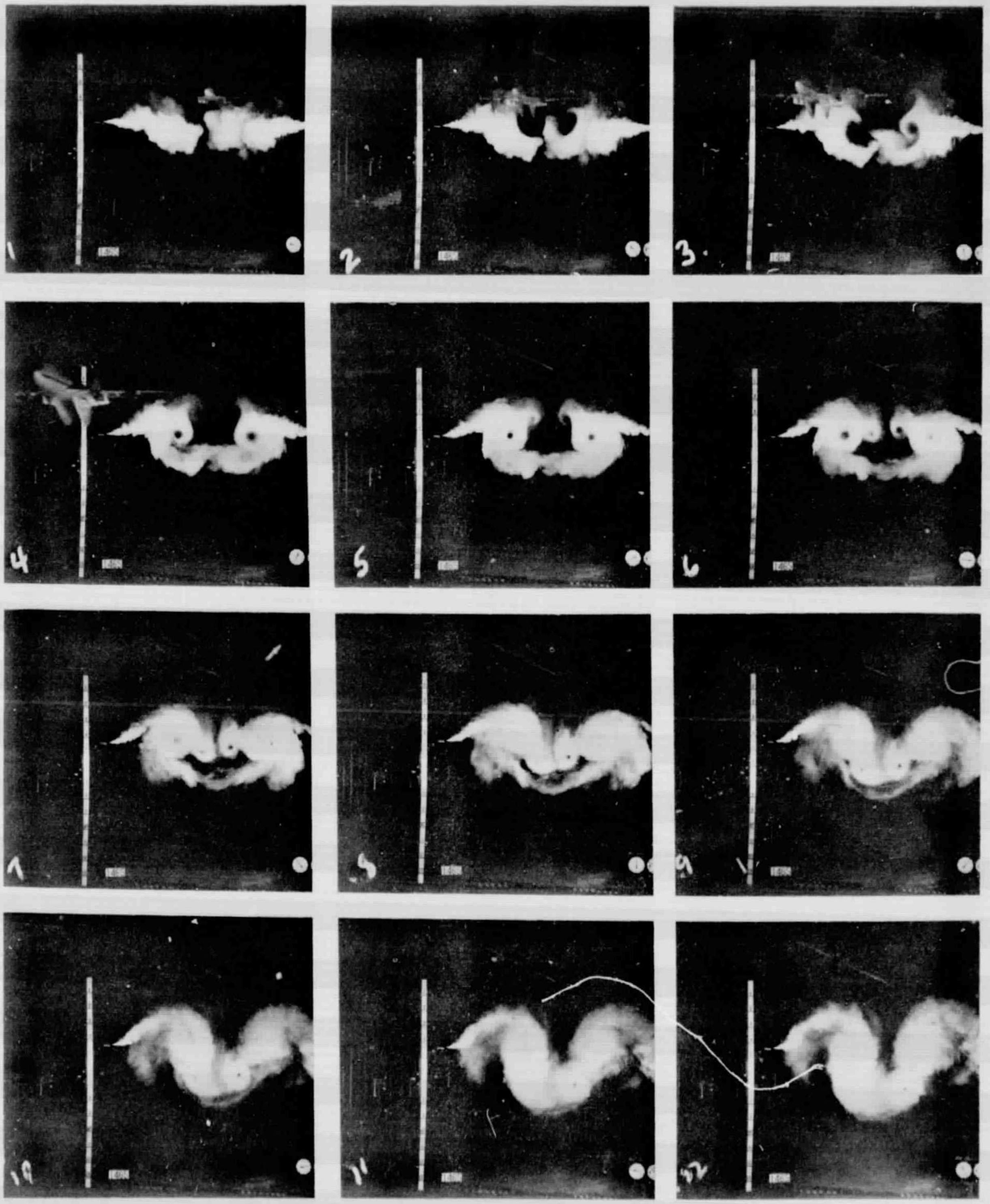

Figure 6. - Visual effect of end plates installed on the inboard edge of the inboard flaps of the Boeing 747. Lift coefficient = 1.2, model velocity ≈ 30.5 m/ second, camera speed = 10 frames/ second.

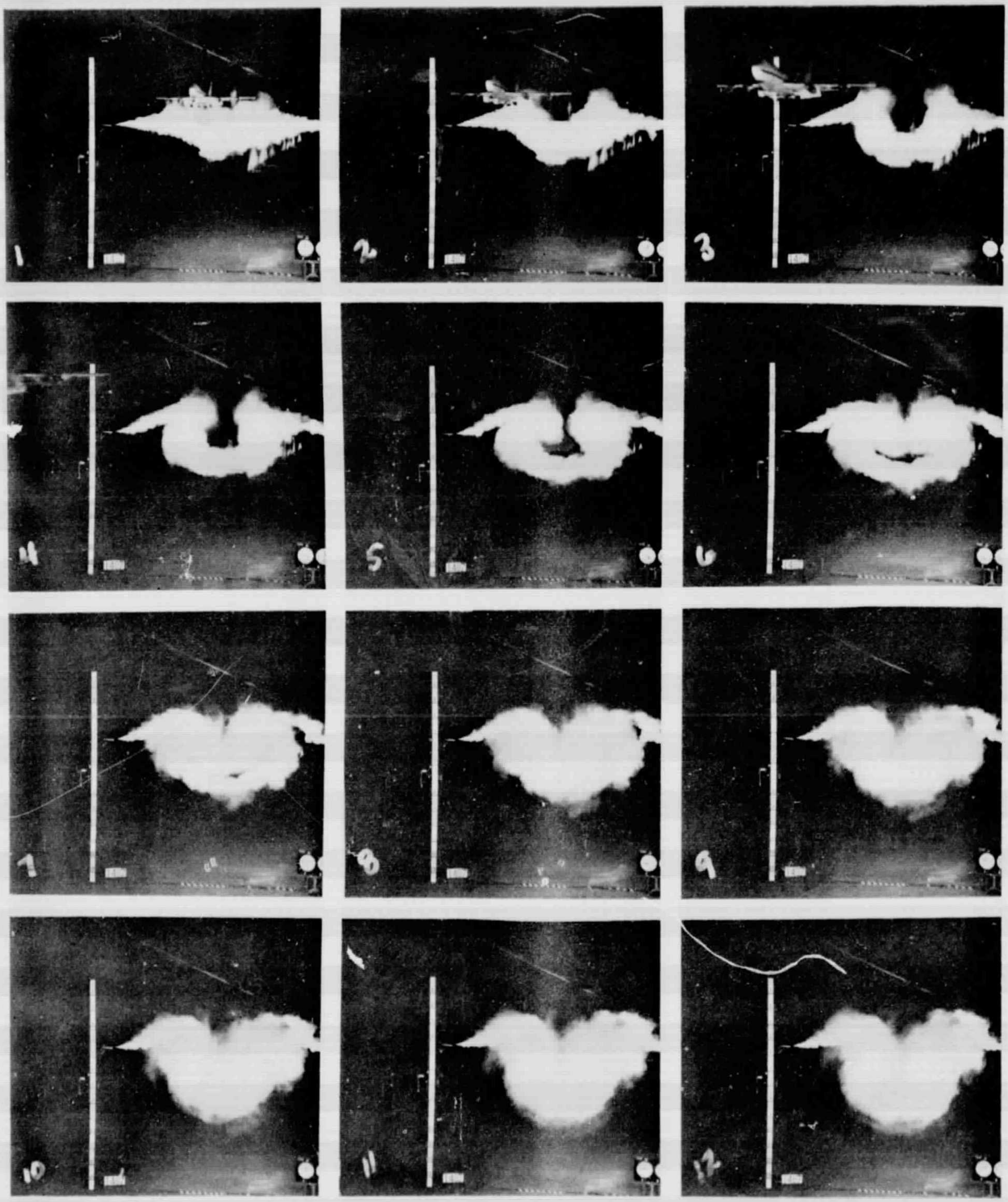

Figure 7. - Visual effect of the fuselage flap on vortex system of the Boeing 747 at a lift coefficient of 1.2. Model velocity ≈ 30.5 m/second, maximum thrust on outboard engines, 6.4 cm diameter disc at each wing tip, camera speed = 10 frames/second.

NASA-Langley, 1975