TWENTY FIRST EUROPEAN ROTORCRAFT FORUM

Paper No. 12-9

Model rotor boundary layer flow visualization with and without partial stall and tripwires

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August 30-September 1, 1995
SAINT-PETERSBURG, RUSSIA

Paper nr.: XII.9

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Summary

This paper presents a consistent set of China clay series of flow visualization on a rigid wind turbine model. Effects of partial stall and trip strips are included. The origin of the study from stall flutter model experiments in the critical Reynolds range is explained. The partial stall is related to model work on rolling aircraft wings and its simulation in the late 1930's. The trip strip investigation reflects interest in the influence of roughness on the extension of the negative damping area during stall flutter, which also occurs at full scale. A yet unpublished boundary-layer flow visualization method is introduced to illustrate bubble behavior near the tip vortex.

1. Introduction

The occurrence of partial stall on wings, rotating or not, is quite common. In some cases constantly present, other wise periodic or transient. Early model tests on rolling wings set the scene in the late 1930's (Ref. 1 and 2). Also from that epoch: root-stall visualization by tufts on an autogiro in forward flight (Ref. 3). Finally reference 4 abundantly illustrates the problem for a large variety of model propellers in water.

In the 1950's interest in boundary layer behavior on a constant chord untwisted helicopter blade - incorporating a NACA 0012 Mod.airfoil- arose in The Netherlands as drag from deceleration tests on a low whirl stand for ramjet development was nearly 50% higher than measured in the wind tunnel (Ref. 5). China clay with methylsilicilate as developer and the lead sulfide streak process releasing hydrogen sulfide from the nose at different radii on a lead-carbonate coated blade side were used for flow visualization. Only one near zero-lift case was investigated so the blade operated in its own wake on the whirl stand. Consequently, the transition location did not differ significantly compared to tests with the same blade in the wind tunnel using China clay as well. Also, no radial effects were detected by the lead sulfide trace technique.
Elsewhere conjectures about contingent centrifugal force effects on boundary layer flow continued, leading to flow visualization studies on main and tail rotors (Ref. 6 and 7). The model work of Ref. 8 and 9 completes these activities by introducing yaw without unsteady influences on a chordwise offset blade rig simulating forward flight to some extent. Also boundary layer trips very near the leading edge were applied on a deviant NACA 0012 tail rotor blade. All these tests included some cases with stall but avoided unsteadiness.

If unsteadiness is introduced- say classical and stall flutter- and studied at model scale (a substantial part of experiments) even on non-rotating models a very intricate experimental situation is present, e.g.:

- low Re numbers, contingently in the critical range,
- the possible presence of tripping devices,
- flow non-uniformity and turbulence of facilities,
- airfoil nose modifications (not to be further addressed).

Probably the oldest worries of model roughness in unsteady wind tunnel tests were expressed in ref. 10. Upper and lower trip wires appear in ref. 11 at Reynolds numbers of 140,000 and 280,000 and in ref. 12 at about $5x10^6$ (also Carborundum grains No. 120 over 4% of the nose) and showed early indications of roughness effects on negative damping in stall flutter.
Another effect of upper and lower trip wires at low Reynolds numbers was discovered in 1950: they suppressed boundary layer instability, e.g. ref.13. In the same year they were applied on a dynamically

scaled rotor model(ref. 14.)
Although Studer (Ref. 15) in his clarifying (stall) flutter model work commenced his experiments with improving the velocity uniformity of the wind tunnel, this, turbulence and for completeness noise, seems to have attracted the least attention.

In model rotor stall flutter tests the situation is even more complex, e.g. ref. 16. For example turbulence becomes dependant on the speed of revolution and the radial coordinate, the translation of the velocity non-uniformity being uncertain. After a substantial flow uniformity and turbulence improvement of the open jet wind facility of the Institute for Wind Energy of Delft University of Technology these factors are considered bypassed, leaving to be explained why trip strips markedly changed stall flutter behavior, at least for torsion excursions below $\pm 1^0$ on the 2 mm. thick Dural flexbeam; the one bladed bearingless model is described in ref. 16. Tentatively it is assumed that the trip strips provoke a change from leading edge -violent behavior - to trailing edge stall giving milder behavior with peak excursions at a lower incidence during stall flutter.
This conjecture receives some support of several findings of ref. 2 and indirectly from ref. 1. Both address the problem of partial stall on a rolling aircraft by using rotating model wings and by simulation through differently twisted wing models. The first used a symmetrical 12.7 % thick Gö 409 section the latter an asymmetrical 17.2% Gö 420 airfoil. The tests covered a Reynolds number range from 150,000 to 220,000.
Ref. 1 succeeds in pressure measurements on the rotating model at different rolling rates anticipating the well-known Himmelskamp effect. The measurements, also on a twisted and an untwisted reference wing in the wind tunnel, show no significant change in maximum lift or stall behavior of the thick Gö 420.

Although ref. 2 rotating pressure measurements failed due to a higher turbulence spot on the wind tunnel axis delaying stall in the middle of the model, the presented dye flow visualization and unsteady pressure measurements in a water tunnel largely compensate this. The findings are particularly interesting as centrifugal and Coriolis forces were absent. Firstly by dye flow visualization a bubble is identified near the stall angle on a zero-twist reference wing (also the unsteadiness of stall is made visible). Secondly transverse flow and pressure changes, particularly in the bubble, on a twisted wing are documented. Finally the effect of a boundary layer fence is recorded. Ref. 2 shows -pressure measurements on several differently twisted model wings in air also taken into account - that twist on the 12.7% thick symmetrical Gö 409 can lead to a change from leading edge to trailing edge stall with some extra maximum lift in the border region of separated and unseparated flow.

2. Background of the study

During attempts in 1984 to check wether the boundary layer instability mentioned in ref. 13 and 14 existed on the ref. 16 model, 0.15 mm. thick trip strips (.015% of the blade chord) from 7-10% of the chord were applied on the upper and lower surface of the blade. Although nothing in that respect could be detected, the strips rose the stall flutter boundary by more than 2° of incidence (as a fact the pressure side strip is not essential) in the unimproved wind facility with about 5% speed non-uniformity. This effect was still present in the improved facility with the speed non-uniformity, reduced to ±1.5%. However stall flutter behavior with and without a trip strip now showed a marked difference in the then covered experimental envelope characterized by:

- tunnel speed less than 6 m/s
- stall flutter torsion excursions smaller than $\pm 1^0$
- tip Reynolds number ranging from 100,000 to 150,000
- reduced frequency about 0.4

Without the trip stall flutter reactions started violently while descending in incidence from the completely stalled situation. With the trip reactions were much milder and peak torsion excursions appeared at a lower incidence. A change from leading-edge to trailing-edge stall provoked by the trip strip was thought possible. Having available a rigid two bladed turbine model with approximately the same blade dimensions, comparable twist (autogiro sense) and operating Reynolds number range plus the same NACA 0012 section, it seemed worthwhile to attempt detecting this by the China clay flow visualization technique supported by tuft images on the opposite blade.
Although this goal was not achieved with certainty, results contribute to the findings of the late 1960's. The twisted turbine rotor blade model with stall at the root (with an appropriate incidence) offers an independent insight in the boundary layer behavior on a rotor (see ref. 3 for example). Moreover the turbine conditions with its expanding wake substantially removes influences from the tip vortex (ref. 6 and 7).

3. Model, apparatus and methods

Wind tunnel
The experiments have been performed in the open jet wind tunnel of the Institute for Wind Energy. The wind generator is depicted and described in ref. 17.

Model
The rigid wind turbine model has been designed for aerodynamic measurements, the geometric following below, including the ref. 16 values.

Specifications of the present model		*ref. 16 values*
Radius:	0.6 m	0.606 m
Number of blades:	2	1
Airfoil section:	NACA 0012	NACA 0012
Root cutout:	0.18 m (31%)	0.18 m
Chord:	0.08 m	0.10 m
Blade length:	0.42 m	0.426 m
Blade twist:	$\theta(r/R)=(6+\theta)-6.67\ r/R$, For $0.3< r/R <0.9$	5.73^0 between root cut-out and R=0.600 m
Replaceable tip:	0.06 m, no twist	

The China clay method.
The well-known China clay technique was used with turpentine as "developer", 0.1 mm thick black foil being applied to one blade. The opposite blade had tufts. The development of the patterns in the China clay during rotation was made visible by using a stroboscope synchronized with the model.

Constraints
The model used was in a calibrated order for some other tests representing a propeller with a tip pitch of 4^0 without wind. So incidence could only be varied by variations of speeds of revolutions and wind. Moreover due to the limited space between the tunnel exit and the model the spraying of turpentine could only be executed from the backside of the rotor (pressure side for the propeller and suction side for the turbine cases). Finally the case with a tip Reynolds number of 300,000 could not be extended to the wind-on condition because of vibrations at 15 Hz.

4. Discussion of results

General

Figure 1 presents a frame of reference showing variation of Reynolds number and the influence of incidence change over the radius for the clean and tripped configurations. The 0,15 mm and 3 mm wide trip strip at 5 and 7% chord position. As in e.g. ref. 8 -on untwisted NACA 0015 model rotor blades- the effect of Reynolds number is modest, incidence dominating. In the clean configuration this is most convincingly demonstrated by the sweep signature over the outer 10% zero-twist of the radius, tip incidence being approximately half the tip pitch (-2^0).

The light fan-like patterns originating near the nose were produced by larger than average China clay particles on the trip strip and approximately indicate the stream line direction. The widening of the tip angle suggests transition, but it is not excluded that an open bubble is present. The non rotating blade case with trip strip at 7-10% chord position and Re=60,000 at the highest pitch with attached flow does not clarify this point (fig. 2b). Tufts are of no help either as they do not discriminate between laminar flow (either inside or outside a bubble) and turbulent flow.

By introducing wind the propeller pressure side becomes the turbine suction side. Figure 3 shows bubbles with the turbine at an off-design condition (clean configuration). Apart from the strobe light reflection in the first two (wet test) pictures there are unexplained events in the bubble. The images becomes even more intriguing as the turbine approaches the optimum advance ratio for this pitch setting (configuration with 7-10% trip strip). The near perfect two-dimensionality proves that the twist leads tot a constant incidence over the radius,however the two band phenomenon needs explanation, fig.4.

By a suitable combination of rpm and tunnelspeed the inner half of the blade can be brought to stall (fig. 5a en b). Compared to the non-rotating case with some stall in the middle (fig.2a) the results are excellent. It is perfectly clear, Reynolds number and mean angle of incidence being identical, that the 2% forward shift of the trip strip completely changes the flow pattern over the entire blade. Realizing that the dynamic model would be vibrating in stall-flutter under the same conditions, it is not excluded that such an extra input may well induce the supposed leading edge to trailing edge stall transition. It is regognized that the fig. 5 results are only slightly more than marginal evidence.

Bubble signature near the tip vortex

The presented results were not selected to emphasize the tip vortex, although some pictures reveal its presence on the blade. From the tipvane project origin of the Institute for Wind Energy all model and full scale flow visualization experiments confirm the insensitivity of the tip vortex to centrifugal forces, as has been noted before.

In rotating model tests at Reynolds number between 50,000 and 350,000, with bubbles regularly present, but non-rotating occasionally, the bubble signature near the tip vortex is persistently -though not always, fig. 4 and 5b show recently obtained exceptions- deviant from the normal signature on finite constants chord wing models with square edges like shown in the root-region of fig. 3a and 3b. By using 0.05 mm thick temperature sensitive liquid cristal foil e.g. from the medical field (suggested by J.M.H.M. van Veen[1] in 1985) this signature is made visible on a non rotating tipvane at Re ~ 85,000 with a high Wattage lamp as heat source outside the wind tunnel jet (fig. 6).

The airfoil shown is a highly modified NACA 23012. The standard NACA 23012 and the 12.6% thick Liebeck LA 2566 section show this signature even more clearly with the China clay method in rotating cases.

[1] Presently working at Stork Product Engineering , The Netherlands

5. Concluding remarks

The boundary layer experiments of the present investigation fit and extend the findings of the late 1960's. The twisted turbine model blade with stall at the root offering an independent insight in boundary layer behavior on a rotor. The turbine's expanding wake virtually suppresses the influence of the tipvortex. The partially stalled blade is very sensitive to a small change in trip strip location (roughness relative height), resulting in a completely different flow pattern over the entire blade. It is not excluded that stall-flutter vibrations may induce a transition from leading-edge to trailing-edge stall. Bubble signature in the vicinity of the tip vortex has been revealed. Finally events in the bubble need more explanation.
In spite of massive efforts in the rotating stall flutter field much remains to be done. The modest contribution of the present study attempts to stimulate further investigation.

Acknowledgment
The author wishes to express his thanks to Mr. S. Toet, who had an active part in the experiments and made the results presentable and to Mr. W.A. Timmer for the stimulating discussions.

References

1. Kohler, M.
Über die Strömungsvorgänge an steil angestellten und überzogenen tragflügeln bei Parallelbeweging und Drehung. Luftfahrt-Forschung (LuFo) 16 (1939), S.158-177.

2. Jordan, P.
Auftriebsberechnung und Strömungsvorgänge beim Überschreiten des Maximalauftriebs. Luftfahrt-Forschung (LuFo) 16 (1939), S.184-197.

3. Bailey, F.J. and Gustafson, F.B.
Observations in Flight of the Region of Stalled Flow over the Blades of an Autogiro Rotor. NACA TN 741, December 1939.

4. Gutsche, F.
Versuche an umlaufenden Flügelschnitten mit abgerissener Strömung. Jb. Schiffbautechn. Ges. 41, 188-226 (1940).

5. Berg, van den B.
Experimenteel onderzoek van de grenslaagstroming op een rotorblad van een hefschroefvliegtuig. Nationaal Luchtvaart Laboratorium Amsterdam, NLL-I A.1449 (1957).

6. Tanner, W.H. and Yaggy, P.F.
Experimental Boundary Layer Study on Hovering Rotors. J. American Helicopter Society, Vol. II, No. 3, July 1966.

7. Tanner, W.H.
Rotary Wing Boundary Layer and related researches. AGARD conference proceedings No. 22, Fluid Dynamics of Rotor and Fan Supported Aircraft at Subsonic Speeds, September 1967.

8. Velkoff, H.R., Blaser, D.A. and Jones, K.M.
Boundary layer discontinuity on a helicopter rotor blade in hovering, American Helicopter Society, AIAA Paper No. 69-197, February 17-19, 1969.

9. McCroskey, W. J.
Measurements of Bounday layer transition, separation and streamline direction on rotating blades. NASA technical note, NASA TN D-6321, April 1971.

10. Kaufmann, W.
Ähnlichkeitsbedingungen für Flatterschwingungen von Tragflügeln. Luftfahrtforschung, Band 16 (1939) seite 21-25.

11. Bratt, J.B. and Wight, K.C.
The Effect of Mean Incidence, Amplitude of Oscillation, Profile and Aspect Ratio on Pitching Moment Derivatives. Reports and Memoranda No. 2064, January 1945.

12. Rainey, A.G.
Measurement of Aerodynamic Forces for Various Mean Angles of Attack on an Airfoil Oscillating in Pitch and on Two Finite Span Wings Oscillating in Bending with Emphasis on Damping in the Stall. NACA Rep. 1305, 1957 (Supersedes NACA TN 3643, 1956).

13. Bergh, H., Tijdeman, H. and Zwaan, R.J.
Theory and Experiment in Unsteady Aerodynamics. Proceedings of the colloquium honoring Hans Georg Küssner on the occasion of his 80th birthday. Institut für Aeroelastik der DFVLR, Aerodynamische Versuchsanstalt Göttingen, September 24, 1980.

14. Timman, R. and Vooren, van der A.I.
Flutter of a helicopter rotor operating in its own wake . Journal of the Aeronautical Sciences, Sept. 1957.

15. Studer, H.L.
Experimentelle Untersuchungen über Flügelschwingen.
Eidgenössischen Technischen Hochschule in Zürich, Promotionsarbeit, 1936.

16. Jessurun, K.P.
Stall-flutter second-flap interaction on a one bladed bearingless model rotor. Twentieth European Rotorcraft Forum, October 4-7, 1994, Amsterdam.

17. Toet, S. And Vermeer, L.J.
Modificaties blaaspijp Instituut voor Windenergie en beschrijving huidige situatie (in Dutch). Delft University of Technology, Department of Civil Engineering, Institute for Wind Energy, Technical Memorandum IW-91094M, 1992.

18. Holten, van Th.
An Analytical Theory for Tipvane Performance and Comparison with Experimental Results. 8th European Rotorcraft Forum, August 1982, Aix-en-Provence, France.

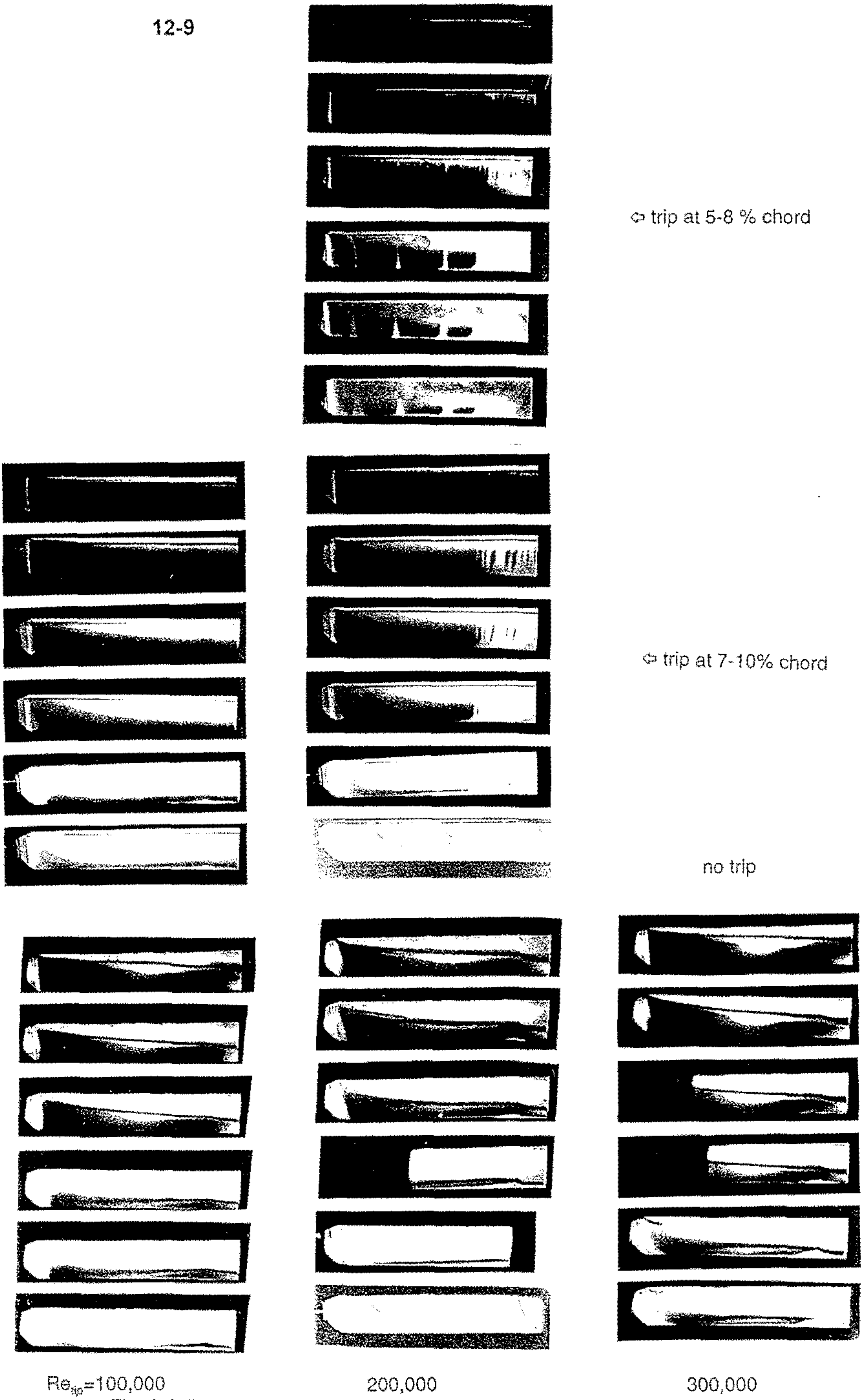
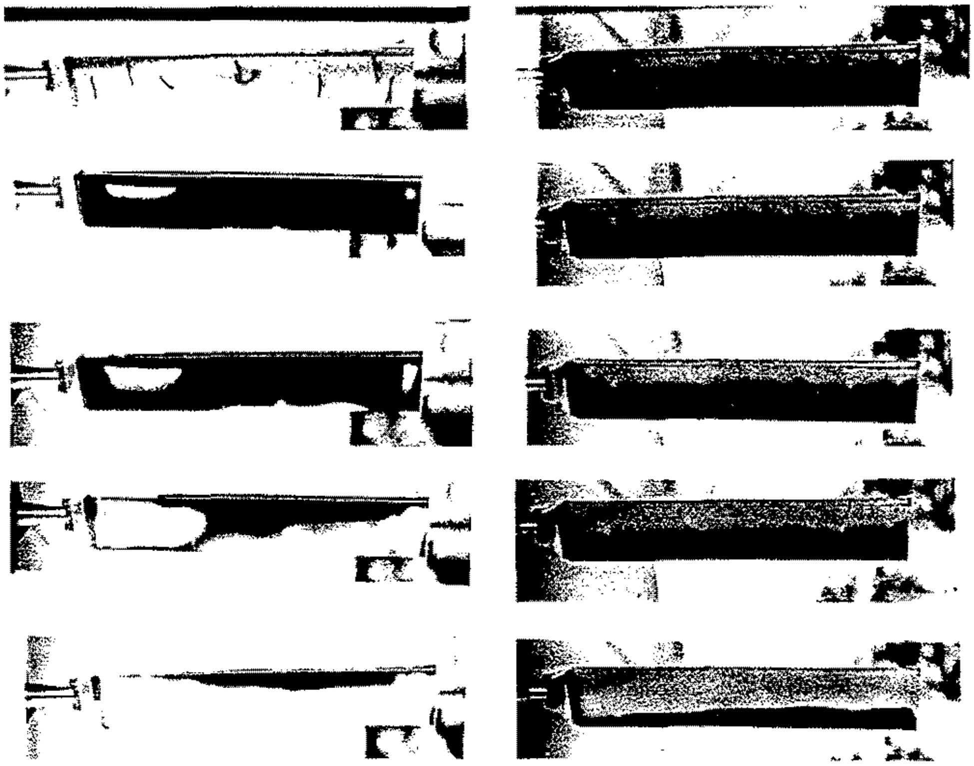
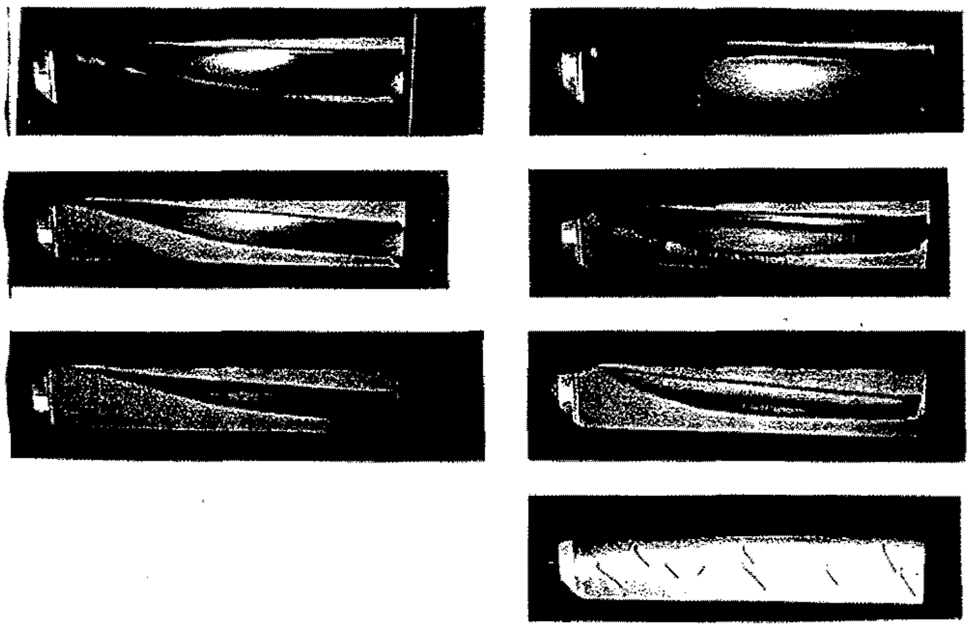


Fig. 1: Influence of variation in Reynolds number and trip strip location



a: start of separation　　　　b: attached flow

Fig. 2: The non-rotating blade with trip strip at 7-10% c at high incidence, Re=60,000



a: Re_{tip}=100,000　　　　b: 200,000

Fig. 3: The rotating blade in the clean configuration

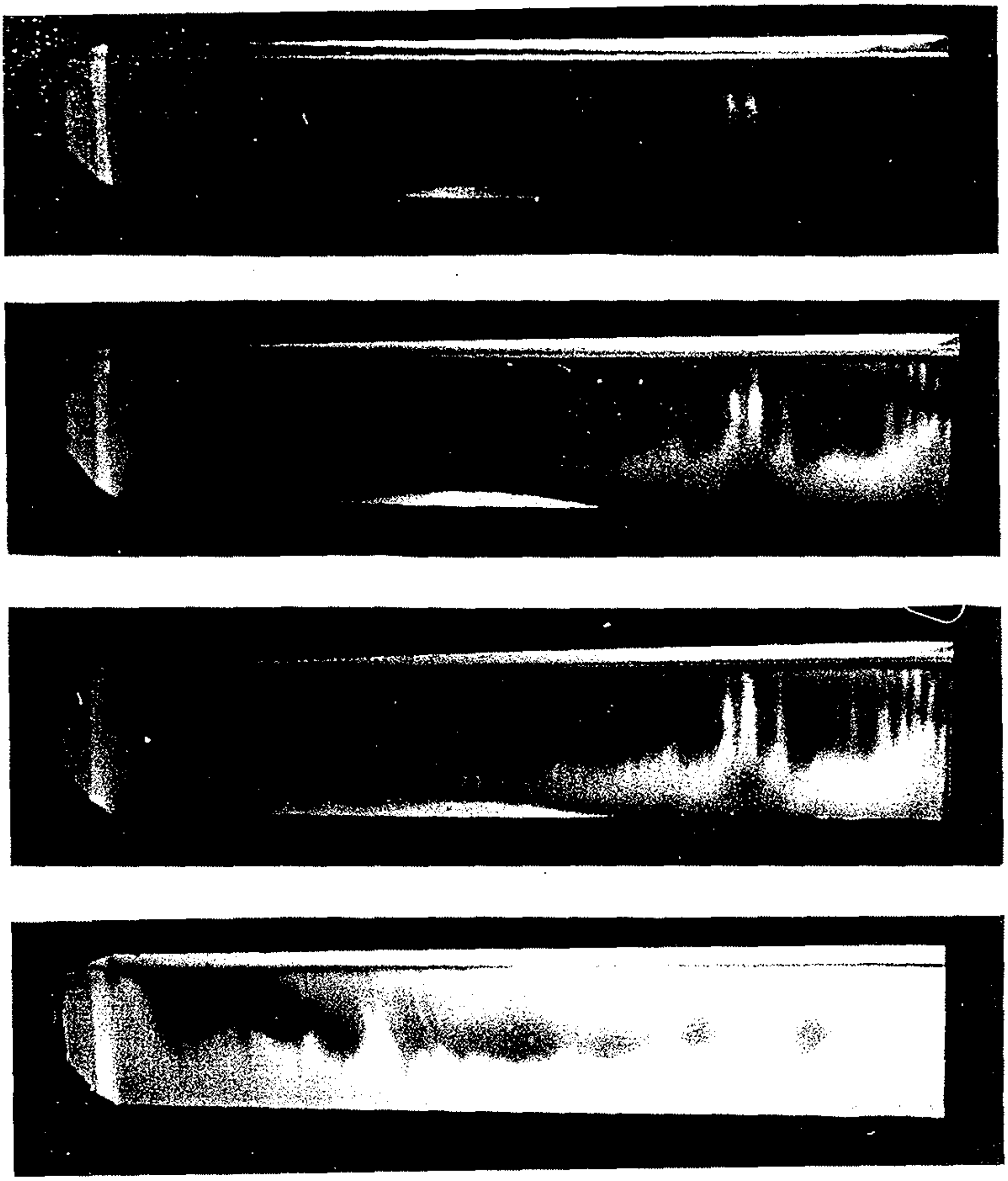
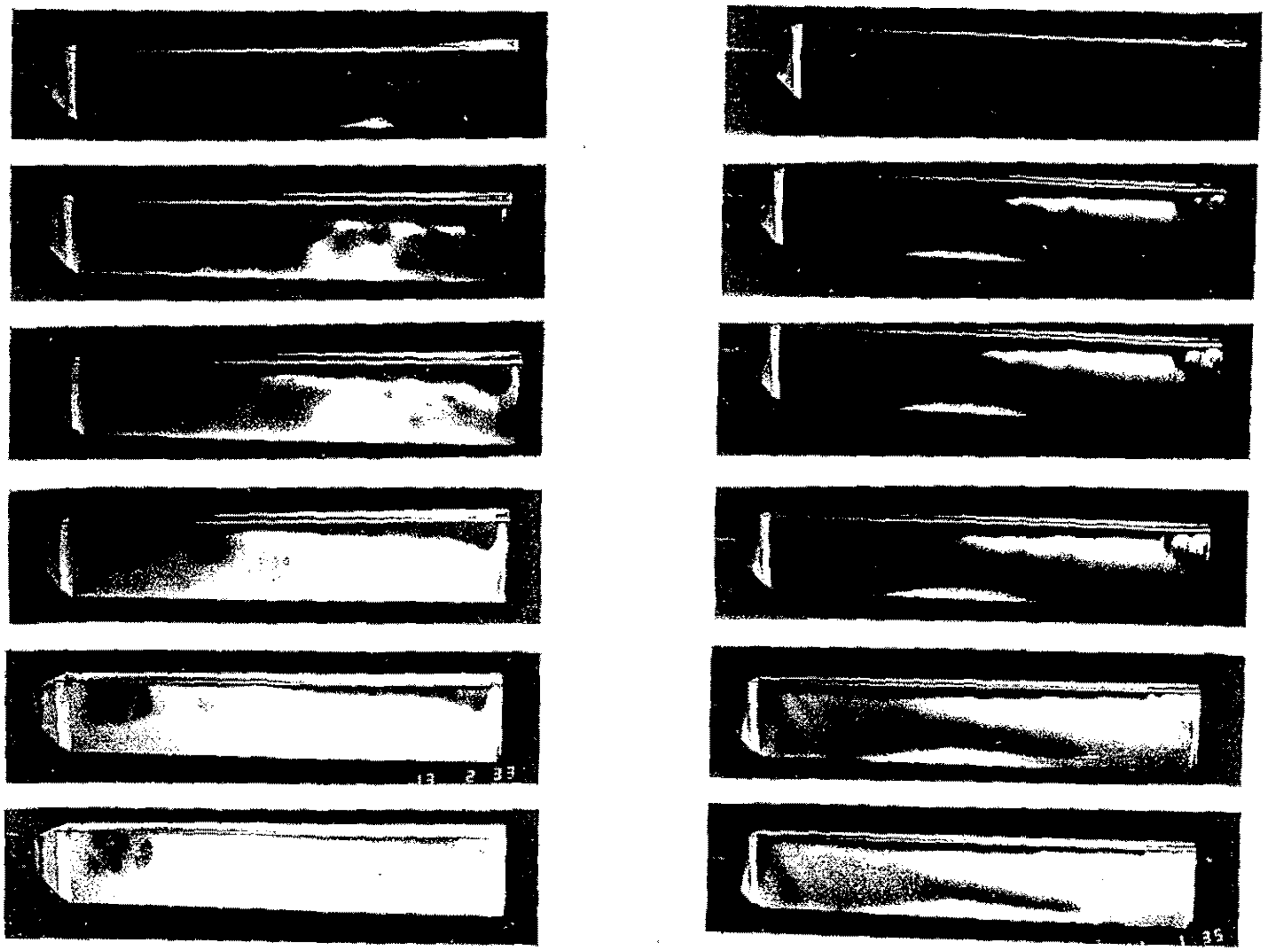


Fig. 4: Evidence of a near-constant incidence over the radius. Re_{tip}=200,000, trip 7-10% c



a: trip at 7-10% chord b: trip at 5-8 % chord

Fig 5: Partial stall on rotating blade. Re_{tip}=100,000, identical incidence

Fig 6: Bubble near the tip-vortex, decreasing incidence from a to c. Re_{tip}=85,000

(a) (b) (c)