Sixth IUTAM Symposium on Laminar-Turbulent Transition

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Volume 78

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The purpose of this series is to focus on subjects in which fluid mechanics plays a fundamental role.

As well as the more traditional applications of aeronautics, hydraulics, heat and mass transfer etc., books will be published dealing with topics which are currently in a state of rapid development, such as turbulence, suspensions and multiphase fluids, super and hypersonic flows and numerical modelling techniques.

It is a widely held view that it is the interdisciplinary subjects that will receive intense scientific attention, bringing them to the forefront of technological advancement. Fluids have the ability to transport matter and its properties as well as transmit force, therefore fluid mechanics is a subject that is particulary open to cross fertilisation with other sciences and disciplines of engineering. The subject of fluid mechanics will be highly relevant in domains such as chemical, metallurgical, biological and ecological engineering. This series is particularly open to such new multidisciplinary domains.

The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of a field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

For a list of related mechanics titles, see final pages.

Sixth IUTAM Symposium on Laminar-Turbulent Transition

Proceedings of the Sixth IUTAM Symposium on Laminar-Turbulent Transition, Bangalore, India, 2004

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Preface

The dynamics of transition from laminar to turbulent flow remains to this day a major challenge in theoretical and applied mechanics. A series of IUTAM symposia held over the last twenty five years at well-known Centres of research in the subject - Novosibirsk, Stuttgart, Toulouse, Sendai and Sedona (Arizona) - has proved to be a great catalyst which has given a boost to research and our understanding of the field. At this point of time, the field is changing significantly with several emerging directions.

The sixth IUTAM meeting in the series, which was held at the Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India, focused on the progress after the fifth meeting held at Sedona in 1999. The symposium, which adhered to the IUTAM format of a single session, included seven invited lectures, fifty oral presentations and eight posters.

During the course of the symposium, the following became evident. The area of laminar-turbulent transition has progressed considerably since 1999. Better theoretical tools, for handling nonlinearities as well as transient behaviour are now available. This is accompanied by an enormous increase in the level of sophistication of both experiments and direct numerical simulations. The result has been that our understanding of the early stages of the transition process is now on much firmer footing and we are now able to study many aspects of the later stages of the transition process. Consequently, considerable light was thrown during the symposium on, e.g., the role of streamwise streaks, flow separation, complex geometry, turbulent spots etc. We are also now capable of better approaches to flow control. The immediate future is likely to see important advances in this area and it is hoped that the symposium has added momentum to this effort.

I am most grateful to the scientific committee for their very active role and detailed advice at every stage. Professor R Narasimha has been involved in each single aspect of the symposium, I am indebted to him for his constant support and guidance. The constant contribution of the organising committee is highly appreciated. It was our good fortune that Anjana Krishnaswamy joined us, she has looked after every detail of both the symposium and of this proceedings in the most professional and meticulous way. I am very touched by the selfless labour put in by the support group, and their high standards, special mention must be made of Faraz Mehdi. All the sponsors are gratefully acknowledged for making the symposium possible. Special thanks to Major Tony Mitchell of AFOSR/AOARD for his encouragement and support. Sincere thanks to the IUTAM. The Pratt and Whitney – A United Technologies Company, Dr. Jayant Sabnis, Dr. Kirit Patel and Dr. TK Vashist have been a constant and important source of support and encouragement. This conference would not have been a success without their active participation.

The facilities and logistics support provided by Jawaharlal Nehru Centre for Advanced Scientific Research is gratefully acknowledged, special thanks to Mr. Jayachandra and his team. Most important, we thank all the authors, session chairmen and all the participants, whose active involvement and contributions defined the conference. Finally, I acknowledge Kluwer-Springer for printing the proceedings.

Countries represented and number of participants

The meeting attracted 113 participants from 15 countries:

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Canada (1)
China (2)
France (5)
Germany (9)
India (49)
Israel (2)
Japan (12)
Malaysia (1)
Russia (4)
Spain (1)
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IUTAM Symposium on Laminar-Turbulent Transition, December 13–17, 2004, Bangalore, INDIA

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Jawaharlal Nehru Centre for Advanced Scientific Research
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LAMINAR SEPARATION BUBBLES

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Abstract: The phenomenon of leading edge stall is associated with the "bursting" of leading edge separation bubbles from a short form, where the length is roughly 100 momentum thicknesses, to a long form that maybe 1000 or more momentum thicknesses long. The paper reports experiments and theoretical discussions of work carried out by the author 50 years ago during his PhD study on bubbles. Detailed measurements of the flow within bubbles are shown together with the oscillogram traces of the velocity fluctuations present. A linear model of the stability of separated shear layers was developed that suggested that the disturbances were spatially evolving waves described by modes with complex wavenumbers and not the temporal modes usually used in stability studies. It was noted that some modes appeared to have a very small group velocity. Although at the time the full implications of this were not properly understood, the conjecture was put forward that a true instability (or absolute instability as it is now called) could therefore exist. A change in the sign of the group velocity could dramatically change the transition process and thus explain the bursting phenomenon.

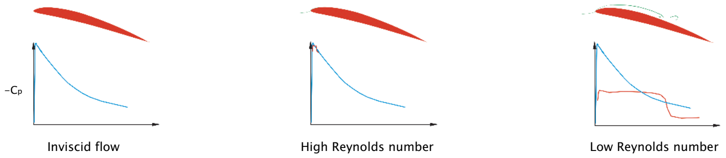
1. INTRODUCTION

Aerofoils designed for extensive regions of laminar flow tend to have small leading edge radii. Such aerofoils have a very abrupt stall characteristic known as "nose stall".

This behaviour is illustrated on figure 1(a) – (c). The potential flow contains a sharp suction peak on the upper surface close to the nose. At high Reynolds numbers, the flow follows the contour closely and separates close to trailing edge. However, if the pressure distributions are examined carefully with very closely spaced pressure tapping around the nose, it is apparent that there is a very small separation bubble present that is characterised by a plateau in the distribution. Oil flow can also show that there is narrow region along the upper surface close to the leading edge

R. Govindarajan (ed.), Sixth IUTAM Symposium on Laminar-Turbulent Transition, 1–13.

where something is happening to the skin friction. On a wind tunnel model this zone maybe only 2 or 3 millimetres long. The turbulent boundary layer that forms downstream of the separated region maybe slightly thicker that that of a boundary layer that has become turbulent via a normal transition process, but this has only a slight influence on the trailing edge separation on the upper surface. Progressive reduction of flow speed will make the bubble longer, but at some stage, the bubble may "Burst" and the separated layer will cover a large portion of the upper surface. The change in flow regime from a "short" bubble to a "long" bubble results in "nose stall".



Inviscid flow

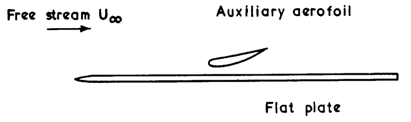
High Reynolds number

Low Reynolds number

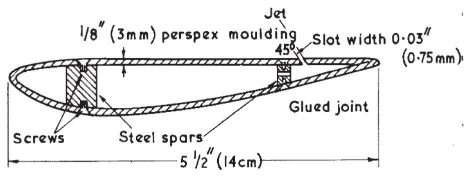
Figure 1. Nose Stall

Apart from some early reference to this behaviour it was not considered to be important until the early 1950's. Owen & Klanfer[1] noted that the short bubble occurred when the Reynolds number of the separating boundary layer was above about 400 (based on the displacement thickness), while the long bubble occurred below this value. This criterion implied that busting was controlled by the stability of the separated shear layer in some way. A number of other papers showed that this simple bursting criterion was not always applicable. Professor Piercy suggested the topic to McGregor[2] in 1951 for his PhD research and he was followed by me[3] and then by several other students. This paper focuses on my efforts during the period 1954 and 1957.

McGregor investigated leading edge bubbles on a Piercy aerofoil, successfully making some pressure distributions as well as hot-wire measurements. The bubble region was quite small and he therefore built a blunt nosed model to provide a physically larger bubble suitable for detailed probe measurements. These were certainly the first measurements of the structure of the short bubble. He did not provide any mechanism for bursting other that a suggestion that the overall energy balance within the recirculation zone could only be maintained by a large expansion of the bubble. My own efforts were directed to the study of bubbles on swept wings. Large swept models require shaped end walls to generate reasonably "infinite" swept pressure fields. An easier way of generating appropriate pressure distributions was to use a plate and auxiliary aerofoil mounted close to the surface. The aerofoil vortex together with the image will create a field that decays like the inverse square of the distance and this reduces much of the end effects. The other advantage of this arrangement is that measurements can be made over a flat surface to a large physical scale for a range of different pressure distributions. In fact, although a swept version of this set-up was produced, I only had time to work with the two-dimensional model shown on figure 2. In order to increase the lift of the aerofoil jet blowing was incorporated.



Aerofoil~Plate setup



Jet blowing aerofoil

Figure 2. Windtunnel Setup

2. EXPERIMENTS

2.1 Mean Quantities

Various pressure distributions were created on the plate and the resulting separated flows explored. An example is shown on figure 3 where the pressure distributions are shown for two speeds that result in a short and a long bubble. The short bubble exhibits a flat plateau, while the lower Reynolds number long bubble shows a slight rise before transition causes the pressure to recover. This pattern is quite characteristic of a long bubble. An approximation to the inviscid pressure distribution was obtained by measuring the pressure distribution when separation has been inhibited by tripping the boundary layer.

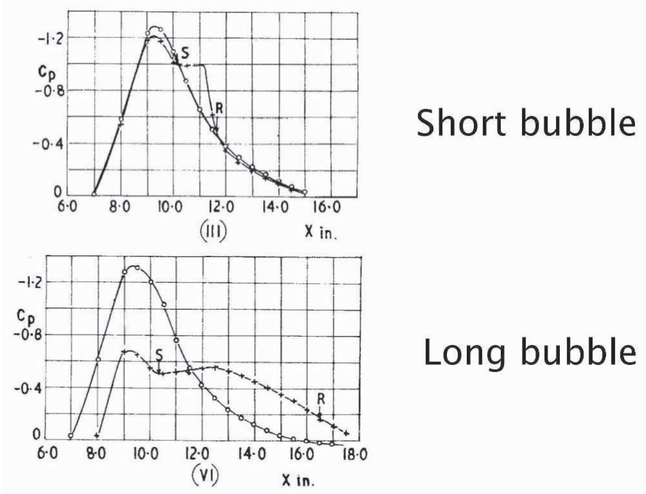


Figure 3. Pressure Distributors

A constant current hot-wire anemometer was used to explore the flow within the bubble. The wire cannot distinguish between forward or reverse flow, and it also gives incorrect mean estimates in regions of high turbulence. A set of velocity profiles for the two pressures distributions shown above are plotted on figure 4. The profiles for the long bubble are drawn with 4 times the scale thus indicating a much thicker separation bubble. This is more clearly indicted in the next figure showing contours of the mean hot-wire readings. Both pictures show an initial triangular region where the velocity, although reversed, is almost stagnant. The laminar shear layer above this region spreads very little before reaching a maximum height. At this point considerable turbulence activity occurs and the shear layer spreads out rapidly as the flow reattaches to the surface. The contour patterns in the two cases are not that dissimilar from one another for the forward part of the long and short bubbles. However, the turbulent reattachment zones are different with the long bubble zone taking a much larger portion of the bubble.

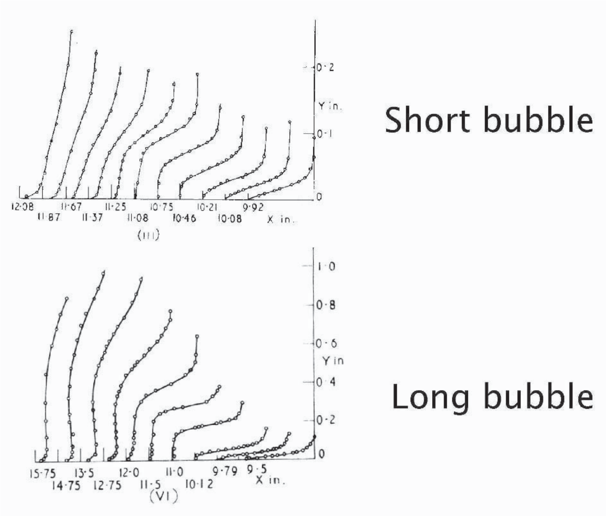


Figure 4. Velocity Profile

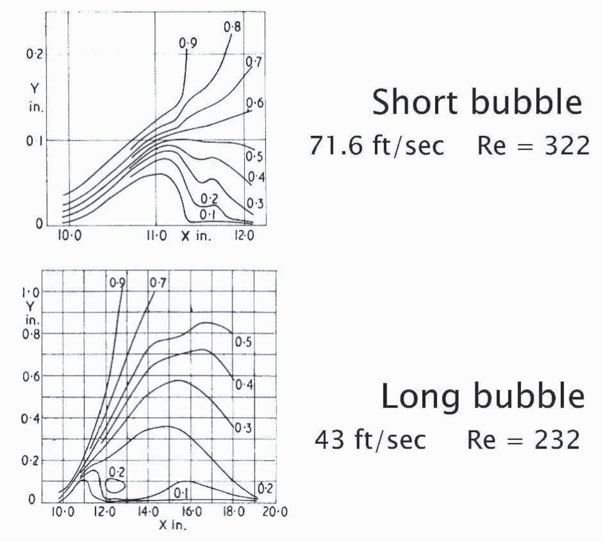
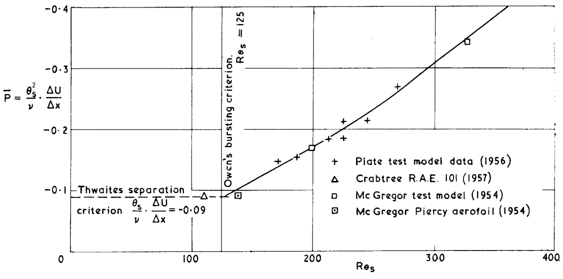


Figure 5. Contours of Hot-wire Signal

The structures of short bubbles prior to bursting as speed was reduced were studied for a range of pressure distributions. It was quite clear that the critical Reynolds number for bursting was highly dependent on the height of the bubble amongst other parameters. Larger pressure gradients caused the bubble height to be greater and this appeared to be associated with an increase in critical Reynolds number for bursting. The height of the separated shear layer is related to the collapse in the pressure distribution arising from the displacement shape of the bubble. A suitable parameter defining this is given in terms of the pressure gradient that would have existed if there were no displacement effect. This pressure gradient scaled with the square of the momentum thickness and the viscosity is plotted against separation thickness Reynolds number at bursting on figure 6. Points from other experiments are also incorporated on the figure and show good consistency.

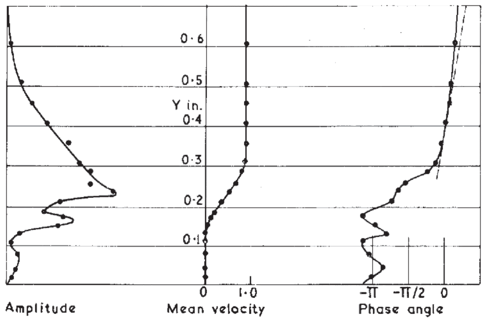


Conditions at bursting

Figure 6. Bursting Criteria

2.2 Unsteady Measurements

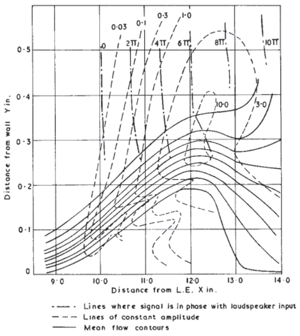
The signal from the hot-wire bridge, suitably amplified, provided information on the transition process taking place in the bubble. It was hoped that a careful examination of the transition processes taking place in the two types of bubble would give some clue as the reason for the phenomenon of bursting. It was noticed that short bubbles were susceptible to external excitation by sound. Even quite a weak tone of the correct frequency could excite a periodic response of the hot-wire in the separated shear layer of a short bubble. The process was so powerful that it seemed sensible to use a loud-speaker mounted on the roof of the contraction to try to excite regular waves that could then be mapped as they progressed downstream. It was at that time known that periodic travelling waves could be generated in boundary layers. The paper of Schubauer and Skramstad[4], that had been published a few years before this work was carried out, showed that the basic instability ideas of Schlichting[5] and Tollmien[6] were substantially correct in explaining the mechanics of transition to turbulence. It seemed likely that the acoustically generated waves were of the same type and it was expected that a proper exploration of these waves in the two types of bubble would explain bursting. Initial measurements were made in a short bubble. In order to obtain the phase and amplitude of the excited wave with respect to signal feeding the speaker a rather complex sequence of operations had to be performed that involved determining the mean square of the sum and difference of the hot-wire and the loud-speaker signals. This was then repeated using a 90-degree phase shifted speaker signal. The squaring operation was carried out with a vacuum thermo-junction tube. A boundary layer traverse with the phase and amplitude is shown on figure 7. This would have taken a whole day to obtain. The phase plot is much more complex than that arising in an attached layer. Note that the outer solution shows an exponential decay for the amplitude that can be used to obtain the real part of the wavenumber, while the phase behaviour provides an estimate of the imaginary part, or spatial amplification.



Amplitude and phase profile

Figure 7. Amplitude and Phase of Excited Wave

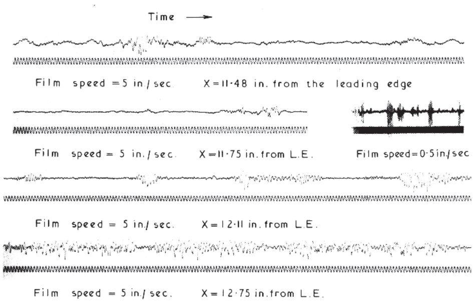
The whole region of a bubble was charted in this way and this is displayed on figure 8.



Phase and amplitude of excited waves

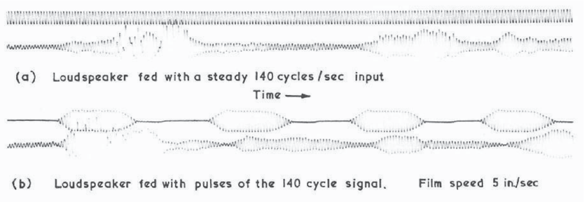
Figure 8. Contours of Excited Wave

Attempts to repeat these measurements on a long bubble failed because it turned out to be impossible to generate regular periodic waves in this type of flow. As this was near the end of my 3 year support it was too late to spend time in further investigation. I treated this inability to follow through my measurements to the long bubble as a failure. Hot-wire traces taken in the long bubble are shown on figure 9 without excitation and on figure 10 with periodic and pulsed excitation.



Hot-wire signals from a long bubble

Figure 9. Hot-wire Signals in a long Bubble

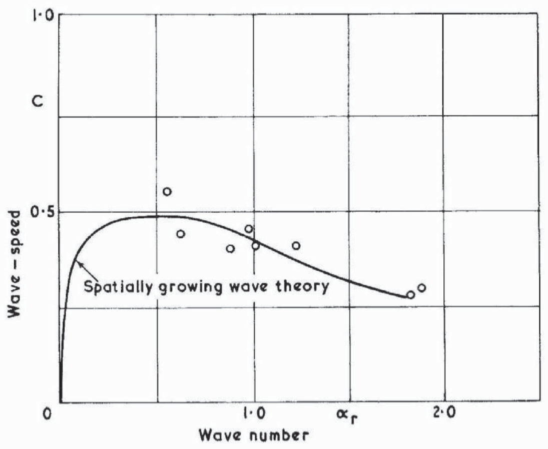


Signals from a long bubble
with continuous or pulsed excitation

Figure 10. Long Bubble Response to Periodic and Pulsed Excitation

3. STABILITY THEORY

Since experiments has shown that the separated shear layer supported unstable travelling waves it seemed sensible to address the problem of the stability of typical velocity profiles arising in a bubble. In the region of the flow where the instability waves amplified, the profiles consisted of shear layer some distance from the wall with no flow in the dead-air zone between the layer and the wall. Although Schlichting had calculated the temporal stability of Blasius flow, it was a daunting task to apply his approach to the separated profiles. A simpler approach was used on a profile modelled by three straight lines. Treating the solution in the three sectors as inviscid it was not difficult to produce a characteristic function defining the eigenmodes. In the model viscosity was included in the wall solution and curvature in the central region where there was a critical layer. Although temporal modes could easily be extracted from the characteristic function, the spatial problem was much harder to resolve. At the time it was necessary to split the equation into real and imaginary components and to find crossing points of characteristics. It was clear that the waves grew exponentially with distance travelled and not with respect to time. This was also true of the waves observed by Schubauer. In cases where the amplification factors are weak it was shown that the two types of mode were related through the group velocity. This is of course a physically reasonably way of looking at spatial growth. However, when the imaginary components are as large it is essential to solve for real frequencies and complex wavenumbers in order to describe the appropriate solutions to the physical situation. At the time this was not an accepted procedure! The eigenvalues did not seem sensitive to Reynolds number and it was unclear how the Reynolds number could have any influence on the stability and thus be linked to bursting. Figure 11 shows the real eigenvalues for a profile close to that of figure 7 together with experimental measurements. The imaginary components also agreed roughly with the predictions.



Measured and theoretical dispersion

Figure 11. Comparison of Theoretical and Experimental Eigenvalues

4. DISCUSSION

Measurements of the flow patterns within bubbles provide some indication of the structure. At separation the shear layer detaches from the surface. At some distance downstream the instability of the shear layer