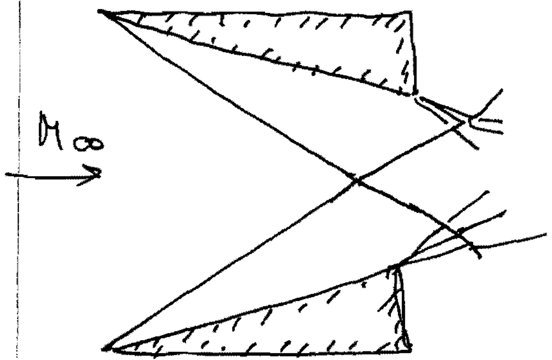
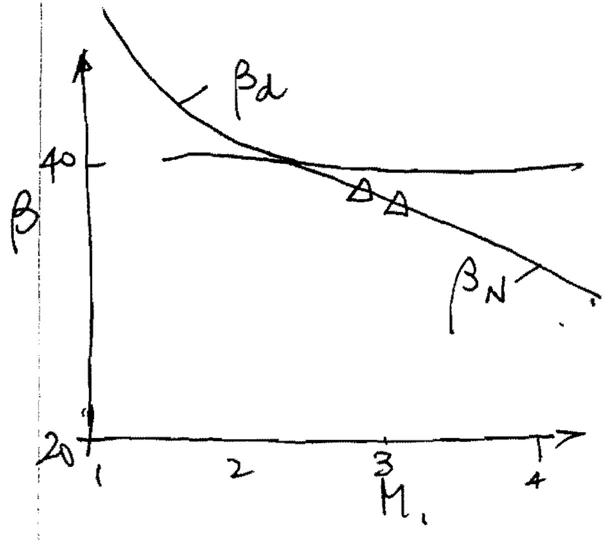
Mach reflection in steady flow.

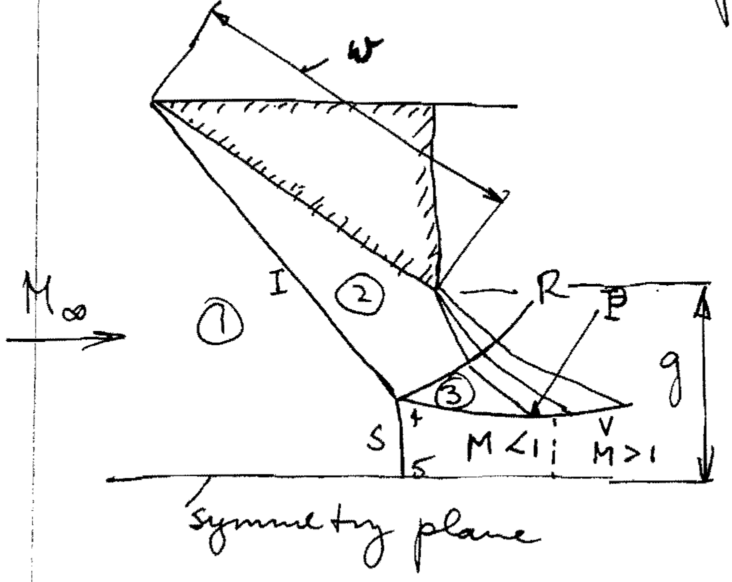
In the mid 70's, Henderson at Sydney University had done some experiments at $M_\infty = 3$ in steady flow, in which he had observed that transition to Mach reflection occurred, not at the detachment condition, as textbooks said, but at what he called the "mechanical equilibrium criterion", known now as the von Neumann condition. At that time, a student of mine (George Kychakoff) and I wanted to use a symmetrical wedge configuration to study dissociative non-equilibrium effects behind regular reflection in the hypervelocity shock tunnel T3 at Canberra, Australia. Because the Mach number of this flow was much larger than Henderson's 3, (in Argon we had up to 16), the difference between β_d and β_N was much larger and way beyond the error bars. It became clear that the transition





criterion for steady flow is different than for pseudosteady flow, in which the information condition gives a convincing argument for the sonic condition to be the transition criterion. Since von Neumann was the first in 1942 to point out that both regular and Mach reflection are possible in the range $\beta_N < \beta < \beta_d$, we referred to the "mechanical equilibrium condition" as the von Neumann condition, a name that has stuck. John Sandeman (a colleague at Canberra) and I had extensive and heated discussions about the difference between steady and pseudo-steady flows, and came to the conclusion that the information condition could explain both cases.

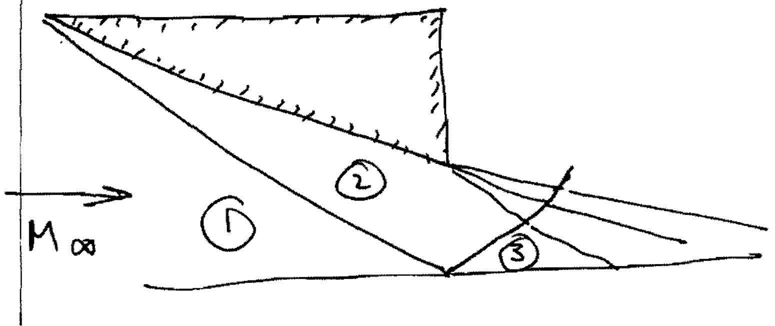
Consider a Mach reflection in steady flow with a symmetrical arrangement of two wedges (avoids boundary layer). In this configuration, the Prandtl-Meyer expansion from the trailing edge of the wedge causes the



reflected shock to curve up. It also becomes refracted as it is transmitted across R. When it interacts with the slip line V, it causes the slip line to curve away from the wall. This causes the stream tube between the slip line V and the wall to have a minimum area at the dashed line. Behind the Mach stem S, the flow is subsonic. It accelerates through the minimum area to supersonic flow. Since the PM-expansion is the agency that causes V to curve away from the wall, the point P at which the most upstream characteristic from the trailing edge of the wedge reaches V lies upstream of the sonic throat. An information path therefore exists between the trailing edge of the wedge and the Mach stem.

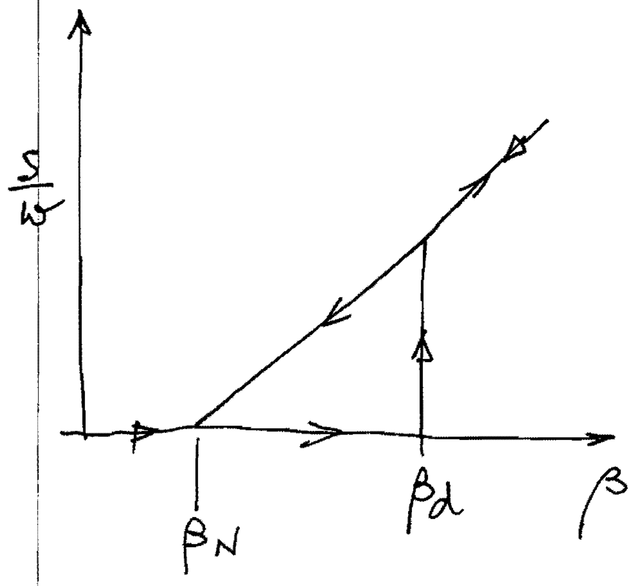
In other words, it is o.k. for the reflection region to exhibit a length scale, since information about both the leading and trailing edge of the wedge reaches the reflection region. To illustrate this more clearly, imagine the scale of the experiment to double, i.e. both w and g to double. Then, in inviscid flow, the only length scales are w and g. Hence the length of S also has to double. It can only do so if ~~it~~ the reflection region knows about both ends of the wedge.

The question now arises as to which reflection configuration will occur in the dual-solution regime $\beta_N < \beta < \beta_d$. In order to understand this, consider the following thought experiment. Let there be a regular reflection in the dual-solution domain, with ③ supersonic. In that case the reflection point can have no knowledge about the trailing edge of the wedge, since the leading characteristic borders a supersonic region 3.



Now give the flow some suitable disturbance so that a Mach reflection temporarily occurs. Such a disturbance would immediately establish an information path to the reflection point, telling it how long to make S. (Note that this mechanism wouldn't help the reflection point to know about the wedge tip in pseudo-steady flow)

These discussions led us to do a whole flot of new experiments that established the difference once and for all (between pseudosteady and steady flow) At the end of the publication of this work in Hornung, Oertel, Sandeman, JFM 1979 I stuck my neck out and predicted that there would be a hysteresis in Mach reflection i.e. that, increasing β from below β_N, the transition to Mach reflection in steady flow would occur at β_s (or β_d) and the Mach stem length would jump discontinuously, while when decreasing β from above β_d, the Mach stem length would decrease smoothly to zero at $\beta = \beta_N$.

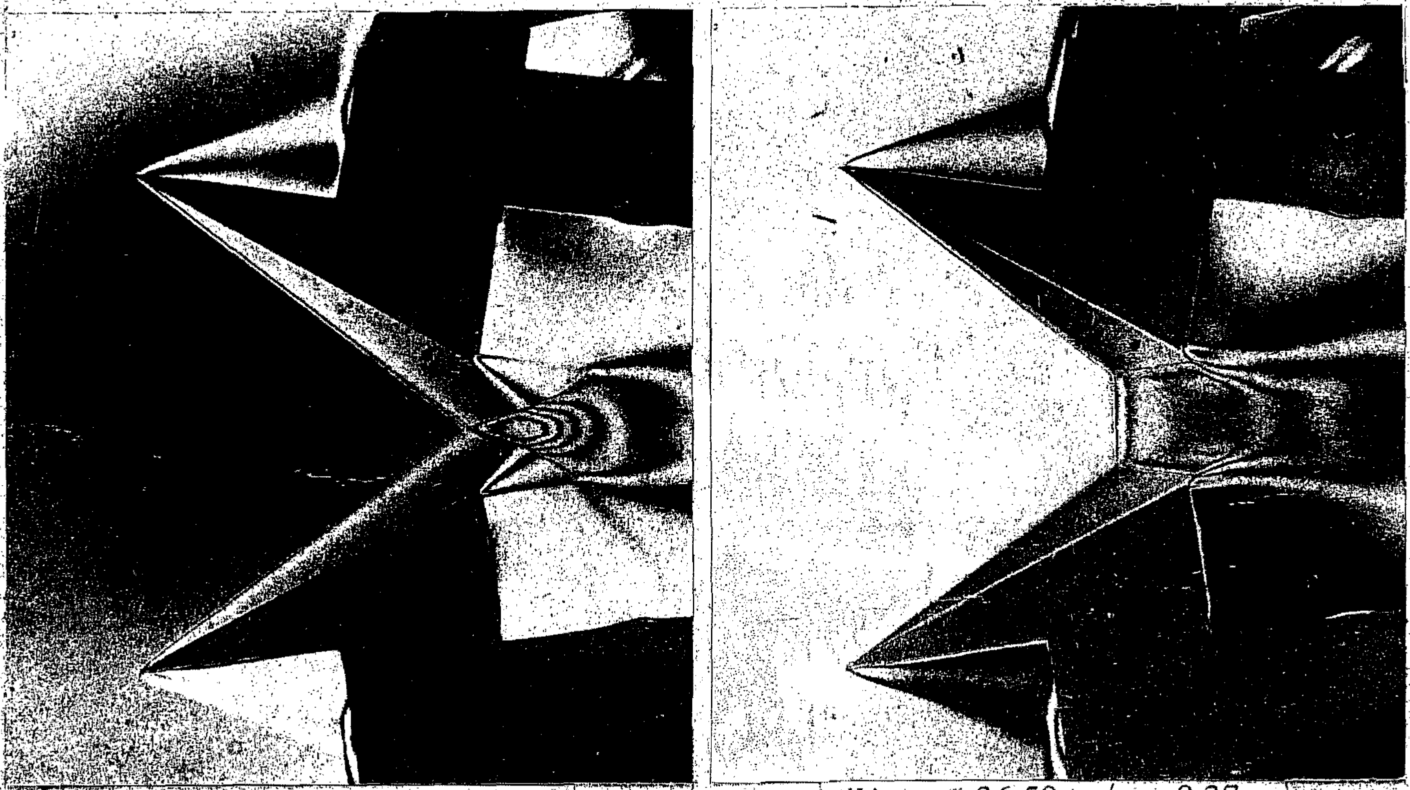


To test this, we did experiments in a continuous tunnel (Hornung & Robinson JFM 1982). We did not observe the hysteresis, but found that transition occurred at $\beta = \beta_N$ in all cases. These are the circular symbols at the bottom of p 187.

In the mid 1990's people started to get interested in the hysteresis again, and now it has been established that it does occur, provided that the wind tunnel is sufficiently free of disturbances. Russian, French, Japanese and German groups have confirmed it convincingly, both experimentally and computationally. It seems from Japanese experiments that dust or ice particles ~~are~~ make the most effective disturbances for causing transition to Mach reflection in the dual-solution domain.

The field has become a real cottage industry There is now a Mach reflection symposium every 2 years and the 15th took place in Aachen, Germany in September 2002.

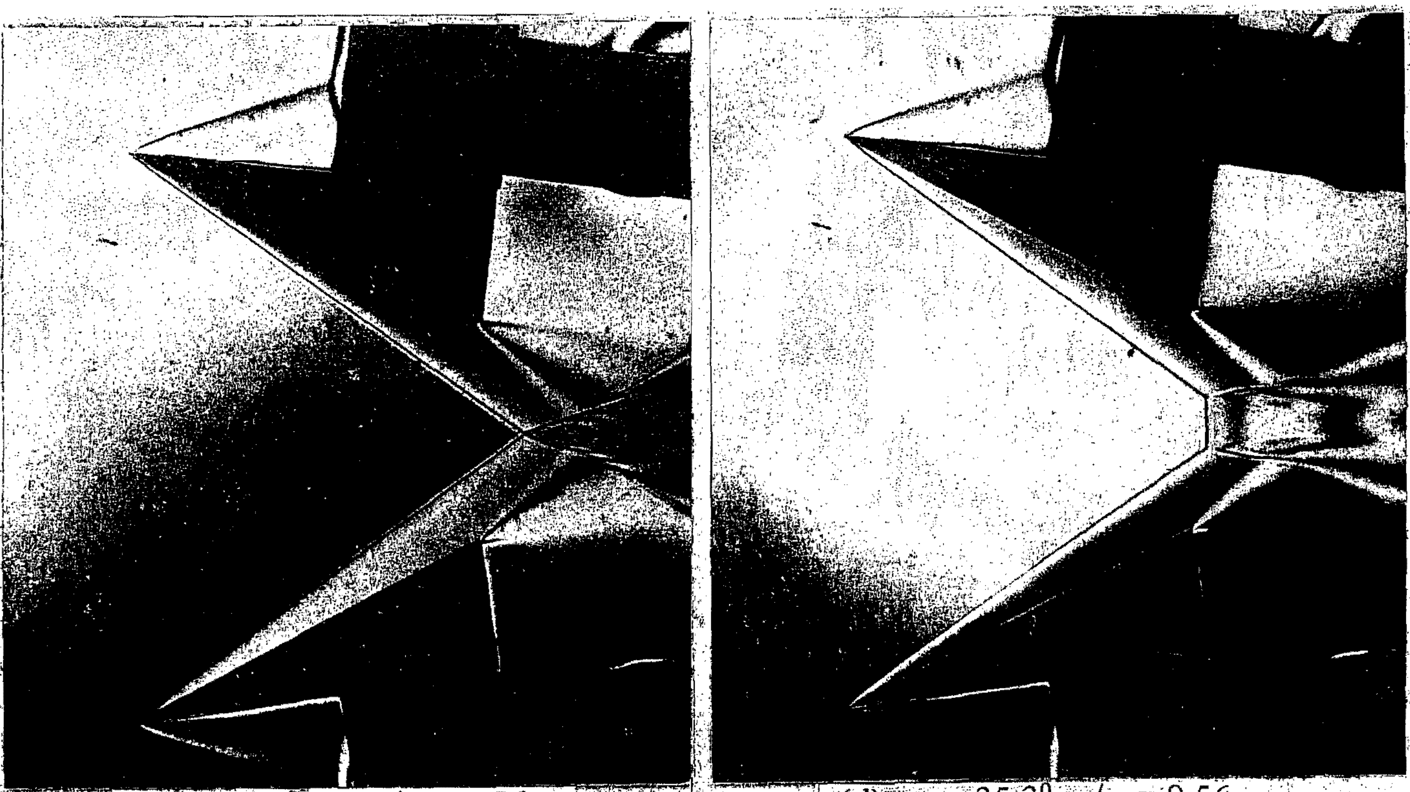
The next 4 pages shows some of the results that have contributed to the history described in the last pages.



(a) α = 36·20, g/w = 0·37

(b) α = 36·50, g/w = 0·37

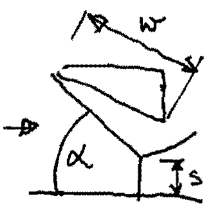
Interferograms of regular and Mach reflection in steady flow. Note how leading characteristic from trailing edge makes the slip line curve to form a sonic throat in Mach reflection.



(c) α = 35·10, g/w = 0·56

(d) α = 35·3⁰, g/w = 0·56

from Hornung, Oertel, Sandeman JFM 1979



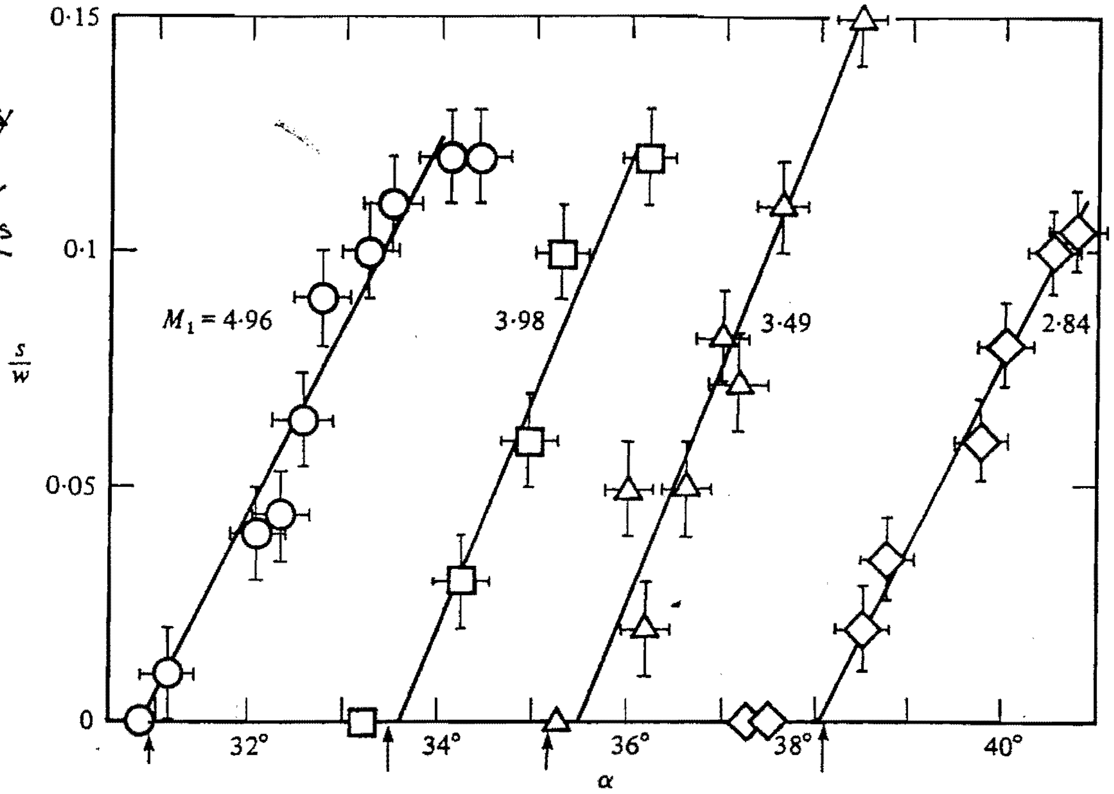


FIGURE 6. Measured dimensionless Mach stem lengths. The straight lines are least-squares fits to the experimental points. The arrows indicate corresponding values of α_N.

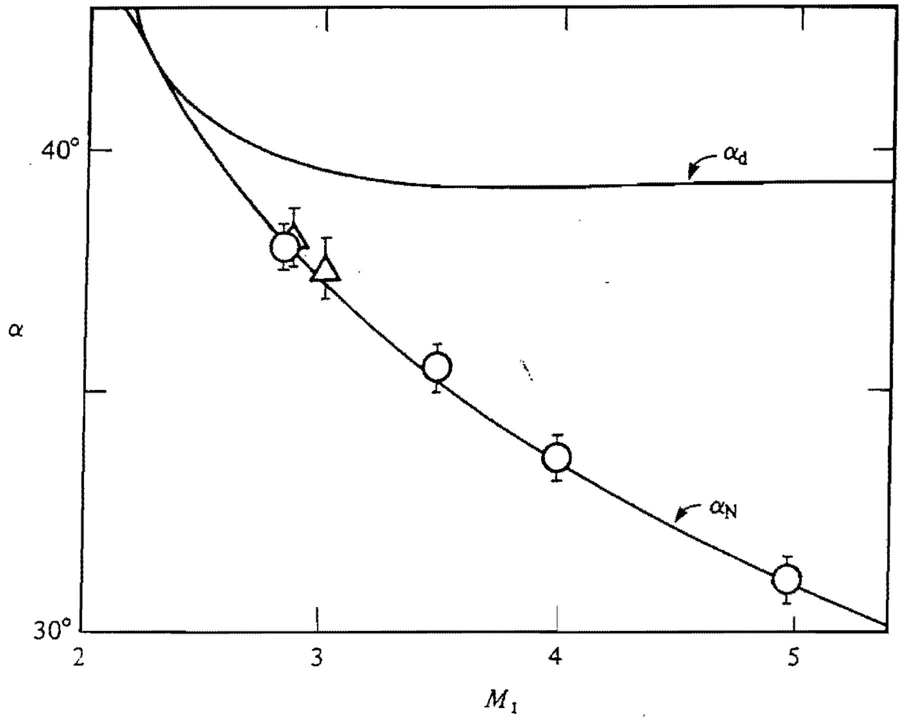


FIGURE 7. Measured transition angle compared with theory. △, Henderson & Lozzi (1975); ○, our data.

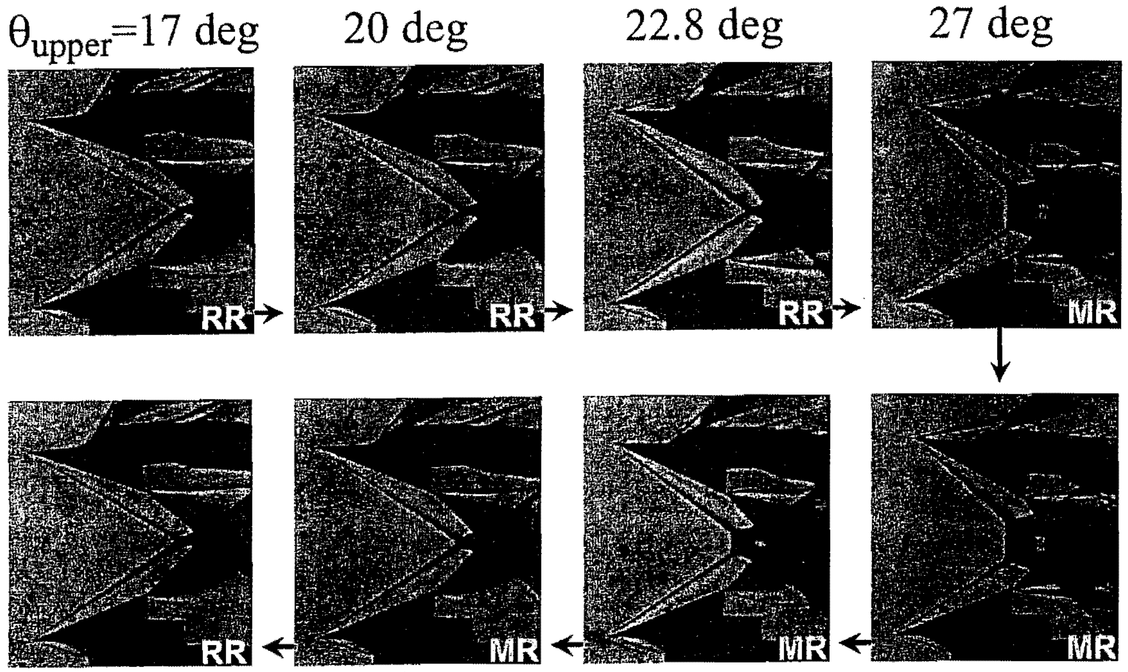
Steady flow experiments to look for hysteresis which was not found. Probably, tunnel too noisy

JFM 1982

Ae237

Previous work (1)

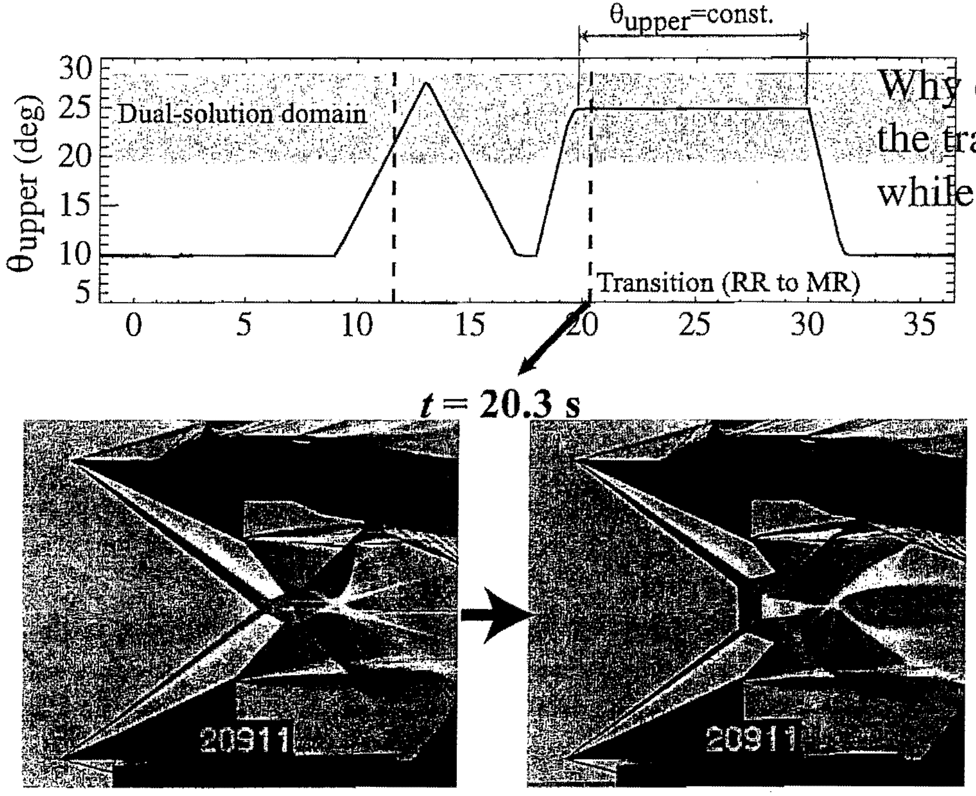
Hysteresis in asymmetric arrangement



(*M*=4.0)

Hysteresis obcerved in experiment Sudani 2002

"Irregular" transition from RR to MR



Why does the transition happen while θ_{upper}=const ?

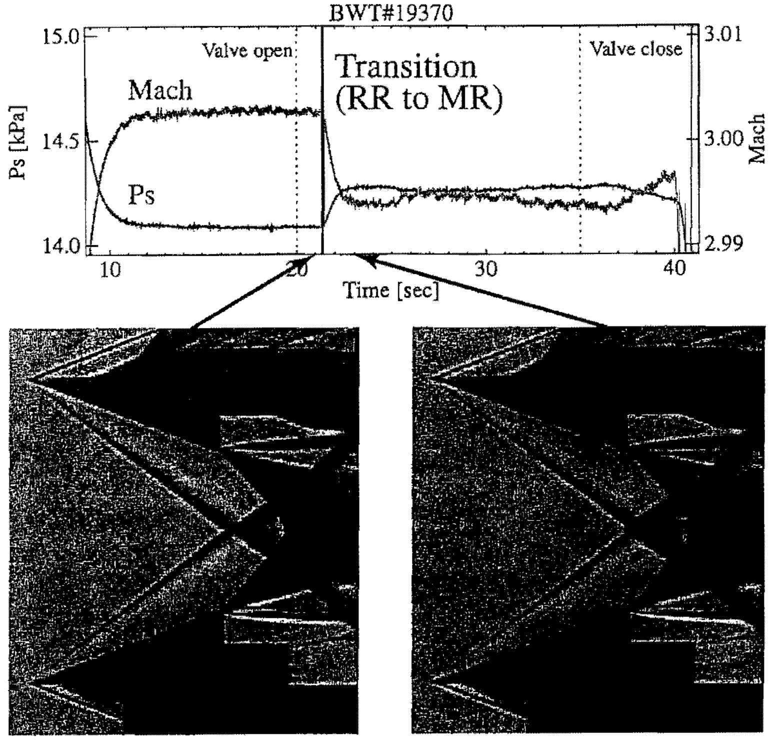
↓

"Irregular" disturbance
or
low frequency disturbance

(*M*=4.0)

Previous work (3)

Effects of water vapors

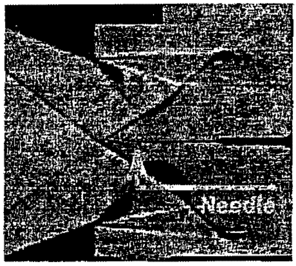


Water vapors
(droplets)
can be causes
for the transition.

(M=3.0)

High speed movie of the transition by a needle

Regular reflection



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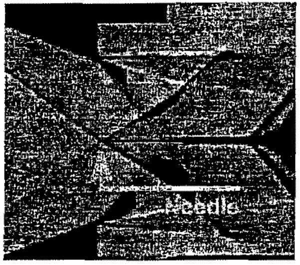
Regular reflection



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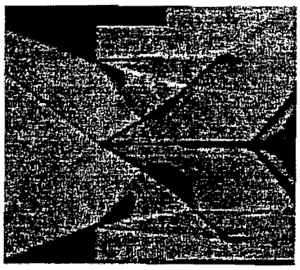
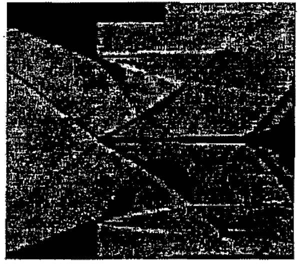
Transition onset



After 0.370 ms



After 0.741 ms

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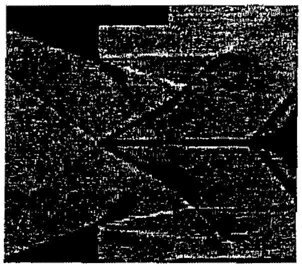

After 1.111 ms

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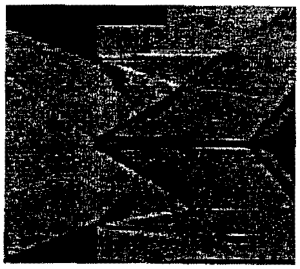

After 1.481 ms