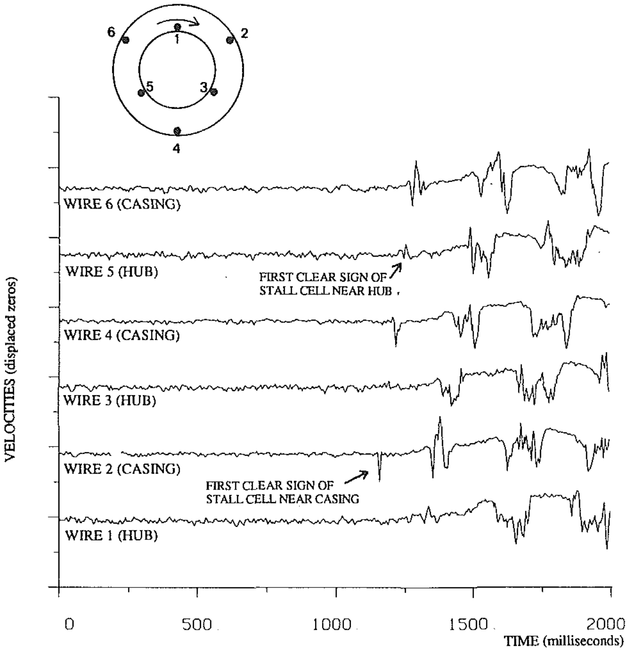

Fig. 16 Time traces from six hot-wires showing the first sign of stall appearing at the casing and not at the hub (tip clearance: 1.2 percent)

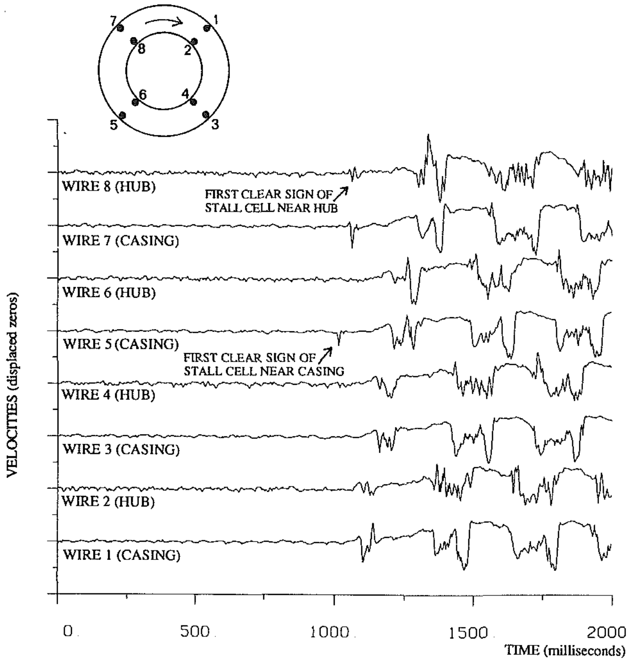

Fig. 17 Time traces from four pairs of hot-wires showing the first sign of stall appearing at the casing and not at the hub (tip clearance: 0.7 percent)

particular, the corners between the two. (My own measurements confirming this picture will be published shortly.)

A flow field such as that illustrated here might be termed "modal" in the sense that the circumferential harmonics of the machine are invoked. These modal oscillations usually become evident near the peak of the pressure rise characteristic. Their presence does not, however, indicate an irreversible or irretrievable downward slide into rotating stall, and at any point prior to the formation of a finite stall cell the flow can be returned to normal axisymmetric operation, without hysteresis, simply by increasing the mean throughflow.

The paper under discussion does make it clear that the presence of detectable circumferential waves does not imply stall, but this needs to be emphasized again because of a misinterpretation of the signals by McDougall et al. The authors placed their probes "just outside the annulus and suction surface boundary layers," the best possible position to detect the modally excited boundary layer fluctuations. These fluctuations are most marked where the boundary layer is thickest, i.e., near the casing for large tip clearances and near the hub for small tip clearances. What the authors failed to do, however, is to show that the stall cell originates from these regions where the boundary layer is thickest. The data reduction technique used in this work, i.e., signal cutoff levels, is unable to distinguish between boundary layer modulations and the formation of a finite stall cell.

Now the reason for emphasizing that early detection of boundary layer excitation is not the same as detecting the onset of stall is that recent measurements that I have made on the same compressor show that stall inception actually occurs at the casing not only for large tip clearances but for small clearances as well. This is a direct contradiction of what is claimed by McDougall et al. in the paper.

The measurements shown in the figures are typical examples obtained on the Deverson compressor in the stationary frame of reference, and consist of traces of velocity versus time as the throttle is inched closed until the compressor stalls. The results are examples of repeated measurements obtained with two fairly small tip clearances (1.2 percent and 0.7 percent of tip chord), both sufficiently small that McDougall et al. would have said that stalling would occur near the hub for this compressor. The hot wires were mounted 20 mm axially upstream of the rotor (tip chord length 108 mm). Six wires were used in one case, eight in the other, with half mounted close to the hub and half close to the casing.

In Fig. 16 the tip clearance was 1.2 percent of chord and it can be seen that steady axisymmetric flow is maintained until time $t = 1200$, at which point a very small stall cell appears near the *casing* on wire 2 and the machine begins its irretrievable slide into rotating stall. The first sign of a stall cell at the hub occurred later at wire 5. In Fig. 17 the tip clearance was 0.7 percent and stall inception was again first apparent near the casing at wire 5, being found only later near the hub at wire 8.

The conclusions to be drawn from this discussion are that, for the compressor used, the breakdown into stall occurs near the casing for all practical tip clearances and is not brought about by boundary layer thickening near the rotor hub. The variation in boundary layer thickness with time found near the hub by McDougall et al. is simply the response of the boundary layer (and possibly of separated flow) to modal unsteadiness in the flow field and is not necessarily the origin of the stall cell.

Authors' Closure

I would like to thank Dr. Day for his comments and note with interest that he has measured circumferential harmonic waves immediately prior to stall on a multistage compressor.

From Dr. Day's comments it is clear that there is some confusion over the difference between the appearance of the first stall cell and the appearance of a disturbance that indicates that the flow is about to break down. The measurements described in our paper were designed to provide information on the flow processes that lead to the breakdown of the normal flow pattern within the compressor into rotating stall. By definition, once a stall cell appears, stall inception has already occurred.

It would seem to me to be extremely unlikely that the rotor passage flow *always* breaks down at the tip, regardless of rotor tip clearance. Measurements made immediately prior to stall within the blade passages (see McDougall, 1990) have shown dramatic changes in the nature of the passage flow, and indeed the overall compressor performance, depending on the tip clearance. I feel it is unwise to attempt to link the radius at which a stall cell is first observed some distance upstream of the compressor face with the radius of stall inception. It is possible that the flow might break down at the hub, and the low momentum fluid associated with the stalled flow subsequently migrate to the tip prior to emerging upstream of the compressor face.

Unfortunately measurements reported in our paper do not give any indication of the detailed fluid mechanical processes of flow breakdown within the rotor blade passages. What has been achieved is a recognition that it is not appropriate to consider the stalling process to be based on a series of random events occurring in individual blade passages. During stall inception, effects occurring with circumferential length scales much greater than one blade pitch are of prime importance. The ability to anticipate the onset of stall using the presence of the small amplitude disturbances may be useful, and there is obviously scope for major developments in this area.