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Investigations Of Blade-Vortices In The Rotor-Downwash

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Abstract

The flow field of a rotor consists of induced downwash, the fuselage wake and the strong rotorblade-vortices. The paper deals with the investigation of those vortices. The trace and the diameter of the vortex were identified by a simple measuring method. This technique was presented in London in 1985. In this paper results of different wind-tunnel investigations, like level flight, descend, climb and transition will be presented and discussed. The tests were conducted in the DNW-Wind-Tunnel using the closed 8*6 m testsection. The test results provide a better understanding of the rotor downwash structure.

1. Introduction

Extensive knowledge about the structure of the downwash is necessary for the theoretical comprehension and the understanding of aerodynamic procedures with the rotor. Mainly it is the more or less big tip vortex which exerts a decisive influence. Contrary to the fixed-wing aircraft the tip vortex does not swim away in a straight line, but gets a helical trace because of the rotating rotorblades. It looks like a twisted cycloid with increasing advance ratio. On the one hand the interference between these vortices and the following rotorblades is important, on the other hand it is interesting to know about the interference with the helicopter tail-groups, the stabilizing fin as well as the tail rotor.

The measurements this paper deals with were carried out during broad downwash investigations with the Rotor Test Rig of the DFVLR Institute for Flight Mechanics. The objective was to find out the position and therefore the trace

of tip vortices. With this knowledge hot wire probes could be positioned at interesting points and the on-line measured data could be interpreted correctly.
To know the positions of the vortices was the actual object of this first part of the measuring program.

Because the results looked so fascinating one could hope to get better knowledge about the structure of the vortices and the downwash itself.
The simple measuring method to use dynamic pressure probes has already been presented in London in 1985 (ref. 1). At that time first findings as well as possibilities of data evaluation were described. Today the entire results of different measuring series will be presented. It will be discussed, whether the great expectations of identifying the vortices were fulfilled and where deductions or improvements could possibly be made.

This paper deals only with the test results. There will be no comparison with any theoretical investigations.

2. Rotor

Measurements were conducted with newly designed rotorblades. It is a hingeless rotor with a diameter of 4 metres. This system correponds - with the exception of the new profile design and shape - with the rotor system of the Bo-105. The shape of a blade is a rectangular trapezoidal wing. The profiles are newly designed (ref. 2). Contrary to the rectangular blades of the Bo-105 model-rotor, these rotorblades will not cause such strong tip vortices because of the shape of the blades.

3. Measuring system

To complete this paper the measuring method will be presented in short :
The facility to measure the downwash is installed on both sides of the test rig. The probes are moving over a sliding carriage system in the X- and Y-direction. A telescopic mast provides the movement in the Z-direction. A view of the measuring equipment is presented in figure 1. An impression of the original facility in the test section is given by a photograph (fig. 2). The driving range of the probe includes the rotor area with an enlargement in the rear zone, the helicopter tail region. Of course, it is only possible to measure below the rotor disc.

At the top of the telescopic mast an arm is installed, holding the respective probe. To investigate the vortex trace, six dynamic pressure probes have been installed in one row, one above each other (fig. 3). The original reason to use those pressure probes to determine the vortices was the fact, that the pressure is very low inside the center of a vortex (ref. 3).

Because of the low pressure it is possible, that vortices, which are passing the probes, can be determined by the measured signals. The probe consists of a pressure transducer which is installed at the top of a tube and is measuring the total pressure. The magnitude of the signal provides information about the location of the vortex related to the position of the sensor. If the probe moves continuously across the vortex field, it is possible to find out the location of the center and possibly the size of the vortex.

Parallel to the pressure signals the position of the rotorblades as well as the position of the probes were recorded on two analog tape recorders and printed out on-line with two slowly moving U-V-paper writers. The interesting field below the rotor was divided into several traces (fig. 4) which the probes continuously followed. The whole field with 17 traces and 6 levels was measured in nearly 13 minutes.

4. Data Interpretation

Four measuring runs are going to be presented. The thrust was kept constant at 3500 N, that means ct = 0.0048. In order to simulate flight conditions the tunnel velocity and the angle of incidence of the rotor disc were varied. The rotor was controlled in a trimmed condition, i. e. the moments at the longitudinal and the lateral axis had a value of zero.

The following measuring runs have been carried out :

1.	Transition	V = 11 m/s	α-Ro =-17 degrees
2.	Climb	V = 33 m/s	α-Ro =-15 degrees
3.	Level	V = 33 m/s	α-Ro = -8 degrees
4.	Descent	V = 33 m/s	α-Ro = 0 degrees

The data recorded on the analog tape recorders were digitized with a sampling rate of 0.4 msec and plottet. The figures 5, 6, 7 and 8 illustrate all the results of these four experiments. The particular figures show the pressure distribution in the corresponding traces on the right and the left side

of the rotor. These figures represent the actual object of the investigations with the pressure probes.
For a quick-look in the wind-tunnel the U-V-strip charts were used, which were produced parallel to the recording on the analog tape recorders (ref. 1) (fig. 9).

Figure 5 contains 18 plots. Each of them shows the pressure signals of the probes in a different x/R position. The adjustment of the rotor simulates a transition flight condition. The tunnel velocity is 11 m/s, the angle of the rotorplane is -17 degrees. In the front position (x/R = 0.9) you can already recognize the influence of the rotor. In this part of the rotorplane at z/R = 0.025 the rotor induces an upwind.
Vortices which show a marked shape can be found from section 3 (x/R = 0.6) onwards. In a distance of z/R = 0.2, that is the fourth trace of this measuring section, the vortex has already left the downwash-cylinder. In the following x/R-positions the trace of the vortex is shifted more and more downwards. In addition to this it is evident, that the vortex looses its intensity. The low pressure signal becomes smaller and more and more indistinct.

Figure 6 shall demonstrate a climb flight condition with V = 33 m/s and α-Ro =-15 degrees. It might be noticed, that the downwash-cylinder has become more flat. Contrary to the preceding figure, in this one the vortex signals do not show the same distinctness.
From the position 10 (x/R =-0.45) on, double signals become visible. In the following positions 11, 12, etc. the distances between the double- or multiple signals of one probe become larger. Such a multiple signal is the beginning of a distinct break in the trace of a vortex. Here the rolling up area of the tip vortex can be seen. The time history of the vortex of this simulated flight condition will be presented later on.

Figure 7 shows the level condition with V = 33 m/s and α-Ro = -8 degrees. In contrast to the preceding figure the downwash-cylinder is shifted more backwards. The pressure signals have become more indistinct. Because of the smaller blade angle on the side of the advancing blade, pressure signals of a vortex can hardly be noticed. However, from a position of x/R =-0.75 onwards, the rolling up area can be made out clearly.

Figure 8 contains just a few vortex signals. Downwash exists only in the upper levels up to z/R = 0.1. Distortion of downwash is visible close to the rotor. Near the tail of the helicopter the distorted wake can probably be found in and above the rotor disc.

The data in the preceding figures form the basis for the presentation of the track of a vortex in constant z/R levels. By this the boundary of the downwash-cylinder is characterized clearly.
Figures 10, 11, 12 and 13 illustrate vortex courses in various z/R-levels.

In figure 10 (transition) the track of the vortex can be seen clearly in all z/R-levels. Therefore the shape of the downwash-cylinder can be made out easily.
However, from the level z/R = 0.2 onwards the vortex signals become more indistinct. A vague rolling up area exists on the levels z/R = 0.3 and z/R = 0.4 from the position of x/R =-0.45 downstream.

Figure 11 (climb condition) also shows clear vortex signals. Especially in those areas where the downwash rolls up, the vortices can be identified distinctly. The pressure signals behind the fuselage from x/R =-0.45 tail-wards result from the fuselage wake. It must be pointed out, that the closer the position of the vortex is to the rotor longitudinal axis (y/R = 0.0) the bigger the diameter seems to be. In the back part of the downwash-cylinder the vortex is active over a large y/R area. The cause of this is the position of the vortex axis in comparison with the measuring line. The more vertical the vortex axis hits the measuring line the more exactly the signal will present the size of the vortex. Figure 14 presents this problem schematically.

Figure 12 (level condition) shows distinct vortex signals only in the rear part. The rolling up area with the multiple signals is already present in the upper level z/R = 0.025. Yet close below the rotor the downwash area is distorted very much. The downwash-cylinder can only be detected by the higher pressure signals caused by the induced velocity in the wake.

Figure 13 (descent condition) shows only three levels. Beneath z/R = 0.1 there is no longer any influence of vortices (fig. 8). Close to the rotor the downwash flows away backwards. In the rolling up area the signals of the vortices can be recognized.

The following is an attempt to present the form of the downwash-cylinders at particular conditions of the rotor, to get information about the diameter of a vortex as well as to follow the trace of a vortex during one rotor revolution. In this paper these investigations will not be accomplished completely for all measured rotor conditions. The amount of data would burst the limit of this presentation and would be suitable only in comparison with theoretical investigations.

The presentation of the pressure probe signals at different z/R levels (fig. 10 to 13) facilitates statements about the shape of the downwash cylinder.

Figure 15 shows the side views of the downwash-cylinders of the four experiments. The information about the boundary of the downwash-cylinder results from the pressure probe signals on the different z/R levels. The rotor conditions of transition and climb (fig. 10 and 11) show excellent signal illustrations close to the rotor. During climb conditions from $z/R = 0.2$ on it becomes more difficult to make a statement about the front boundary. Distinct vortex signals no longer mark the downwash area in the front part. On the contrary there are now little oscillations in the course of the pressure signal which hint at the downwash-cylinder.
The same figure also shows the rolling up areas which are situated at the side of the downwash-cylinders.
During transition the rolling up can be noticed only very weakly in greater distances to the rotor. A more distinct area exists during climb flight condition. In this case the rolling up area flows away downwards.
In level condition the rear boundary of the rolling up area is close to the rotor. The front part of the downwash-cylinder is noticeable only very vaguely.
In descent flight condition the situation is similar. Only in the left rolling up area distinct vortex signals can be discovered. The downwash flows away between rotor and $z/R = 0.1$.

As an example of tail rotor positioning the tail rotor of the Bo-105 is entered behind the main rotor. In transition flight case the rear boundary just flows past the tail rotor. In reality the vortices of the main rotor might hit the tail rotor in the outer area because of the induction of the downwash. In the other cases the tail rotor vortices fully hit the tail rotor. In the tested flight conditions stabilizing fins which are usually situated in front of the tail rotor are not hit by vortices.

Figure 16 shows increased pressure signals. These signal representations derive from transition condition on a level of $z/R = 0.025$. The center of the

vortex is situated in the middle where the signals in negative direction are the largest. The diameter of the vortex is assumed at a position of about 30% of the largest value of the signal (ref. 1). Here it amounts to about 33 to 44 mm.
When measuring the size of the diameter it should be considered that the vortex hits the measuring line inclined or oscillates in position from one rotorblade to the other. These oscillations exist and can be proved with the help of some vortex illustrations (trace 4, $x/R = 0.45$).
The signals in trace 4 show two distinct even drops in pressure at a distance of about 10 mm. Such phases can also be observed in other vortex illustrations.
Trace 8 ($x/R = -0.15$) and 9 ($x/R = -0.30$) contain only reduced signals.

Figure 17 shows the signals in a position of $x/R = -0.6$ at different z/R levels. It can be noticed, that this vortex has an essentially smaller diameter of about 20 mm. Contrary to the preceding figure this one shows another condition of the rotor. Moreover all forms of pressure signals of vortices can be seen. At a distance of $z/R = 0.1$ and below alternating pressure signals are measured : on one side low, on the other side high pressure. High pressure results from the fact that the velocity vector on one side of the vortex points directly into the probe (ref. 1).
To calculate the diameter of the vortex the difference between the highest and the lowest pressure signals is measured and multiplicated by 2. On the lower level of $z/R = 0.3$ oscillations of the vortex traces with a size of up to 40 mm can be noticed.

The reasons for the differences in the shape of the vortex pressure signal can be found in the periodical changing of the angle of incidence of the blade tip, the lagging and flapping motion of the blade, in the direction the axis of the vortex hits the measuring line and in small but noticeable trace oscillations of the vortices.
To get the time history of a vortex, the pressure signal must be highly resolved. Figure 18 shows an example. The signals of the first three probes can be identified clearly. Above these signals the corresponding signal of the rotor phase is drawn as a ramp signal. To determine the position of the rotor the time from the beginning of the ramp to the top of the vortex signal is measured.
At this point you have to answer the question which rotorblade the signal belongs to. The mistake which may result can be 90 degrees or a multiple of it. Also the signals of the following probes cannot be attached definitly to

a special rotorblade. What signal in the following trace is the one of vortex A ? B can be eliminated at the beginning, because it comes too early. Yet C, D and E are for choice. The difference in phase is 90 degrees. Or is it B, but 360 degrees later ? Only the gathering of rotor azimuth angles of the pressure signals in several traces (x/R) and levels (z/R) produces enough data to get a threedimensional impression of the events.

The cut out of one measuring run (climb flight condition) shall give an example for the possibility of following the trace of a vortex during one rotor revolution. Figure 19 shows the track of a vortex in six measuring sections (x/R). This track is presented in the positions y/R and z/R over one rotor revolution. You can compare the azimuth angle with the time. In section 10 (x/R =-0.45) a disturbance of the trace of the vortex starts, which leads to a rolling up. In the following the trace is distorted more and more. The figures on the right show the position of the vortex signals below the rotor as they were measured. The line between the points follows the trace of the vortex in this section. These figures are no projections of the vortices into the plane. In section 11 and 13 the vortex reaches up to a measuring line without going through it. Small low pressure signals point this out.

5. Summary

The objective of the measurements was fully reached by finding the positions of the vortices below the rotor. It is a by-product of these measurements to get more information about the vortices. The downwash-cylinder below the rotor can be measured out in its position very well if the advanced ratio is not too big and if there is not too much disturbance of the downwash. You can notice very clearly the rolling up of the wake. Especially the influence on the tail of the helicopter can be studied. It is likely, that without any problems corresponding measurements can be accomplished at the flying helicopter if the measuring equipment is installed only at the tail.

It has also been possible to get more knowledge about the diameter of the vortex. Whether this can be evaluated depends on the age and the orientation of the vortex.

In order to get a spatial and temporal impression of the vortex trace it is necessary to produce a time history of the signals. To do so is quite bothering, but on the other hand worth-while, if a comparison with a Free-Wake-Model can be made.

It is difficult to identify the rotorblade which belongs to the vortex; this problem can be solved only by comparison of data, combination and logic.

It would be very helpful if one rotorblade distinguished itself by a special vortex signal.

To study the effect of the rotorblade shape the same measurements should be repeated with the rectangular rotorblade of the Bo-105.

As a conclusion of these investigations it is to say that it would be desirable to draw comparison with a usable Free-Wake-Model.

References

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3. J.P.Crowder — Wake Imaging System Applications at the Boeing Aerodynamics Lab. SAE Technical Paper Series 851895, Aerospace Technology Conference & Exposition, Long Beach, California (1985)

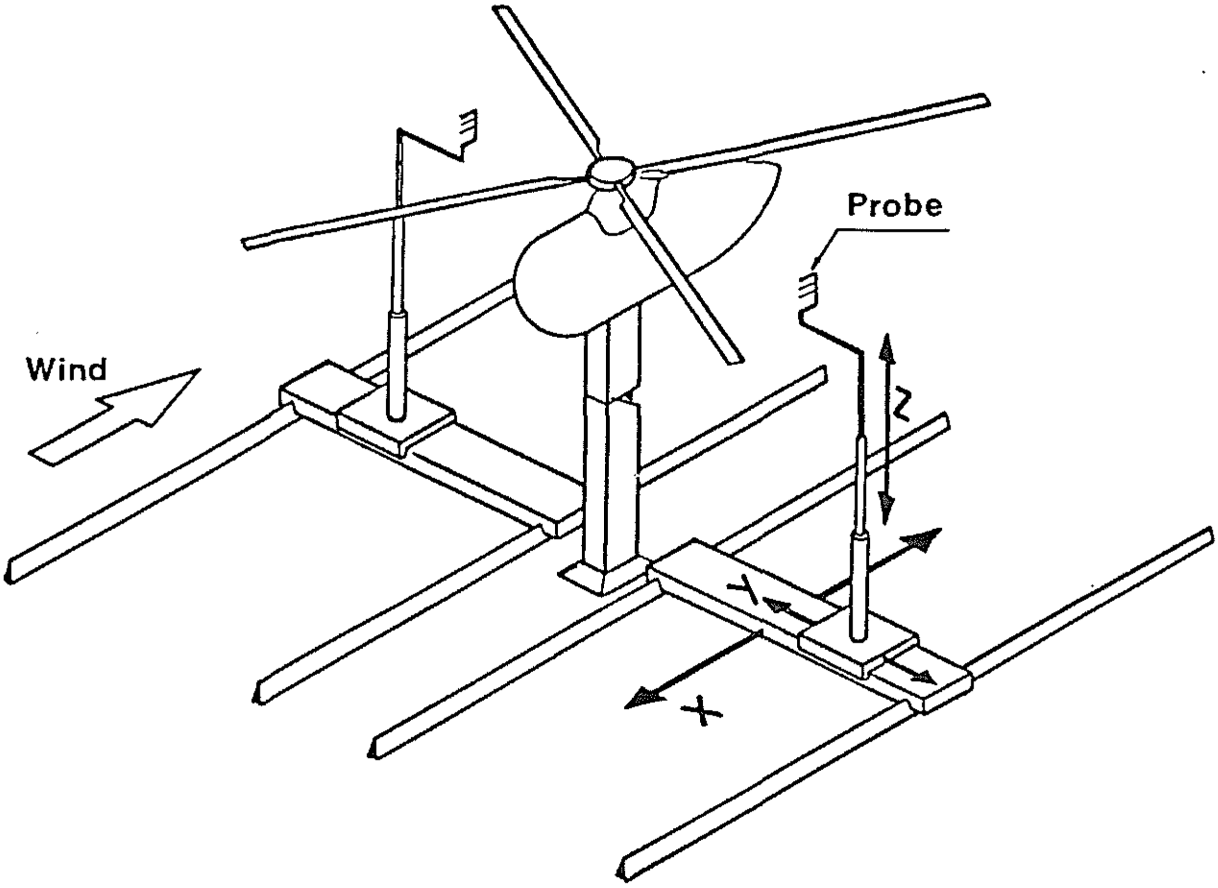

Figure 1. DFVLR-Rotor-Test-Rig with the
downwash measuring equipment

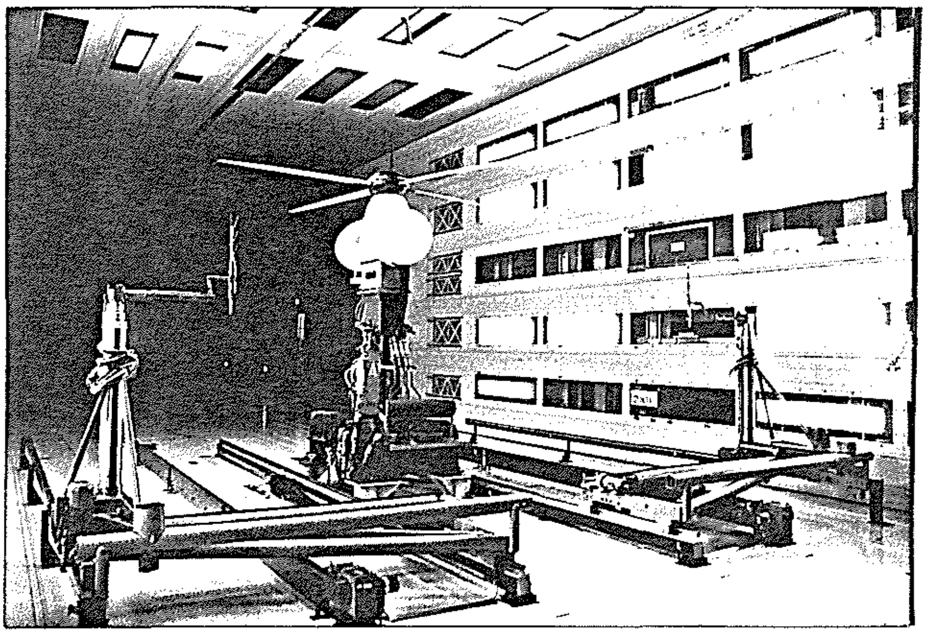

Figure 2. DFVLR-Rotor-Test-Rig with the 4 m rotor
German Dutch Windtunnel
8 x 6 m closed testsection

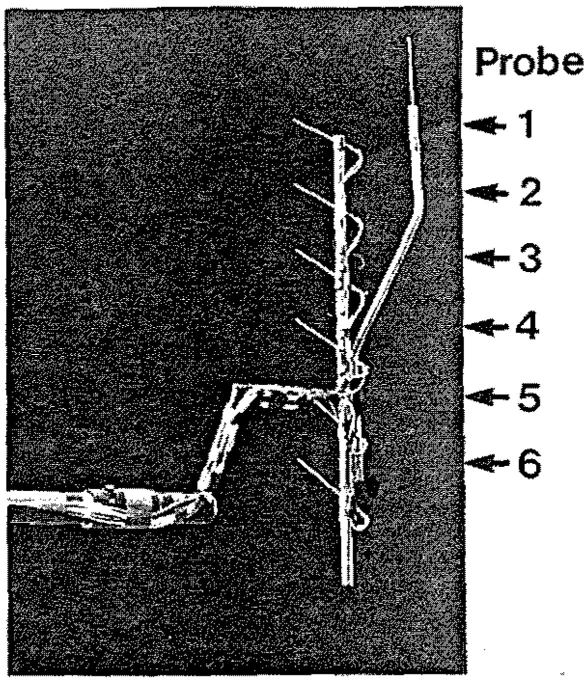

Figure 3. Dynamic pressure probe rake with 6 sensors

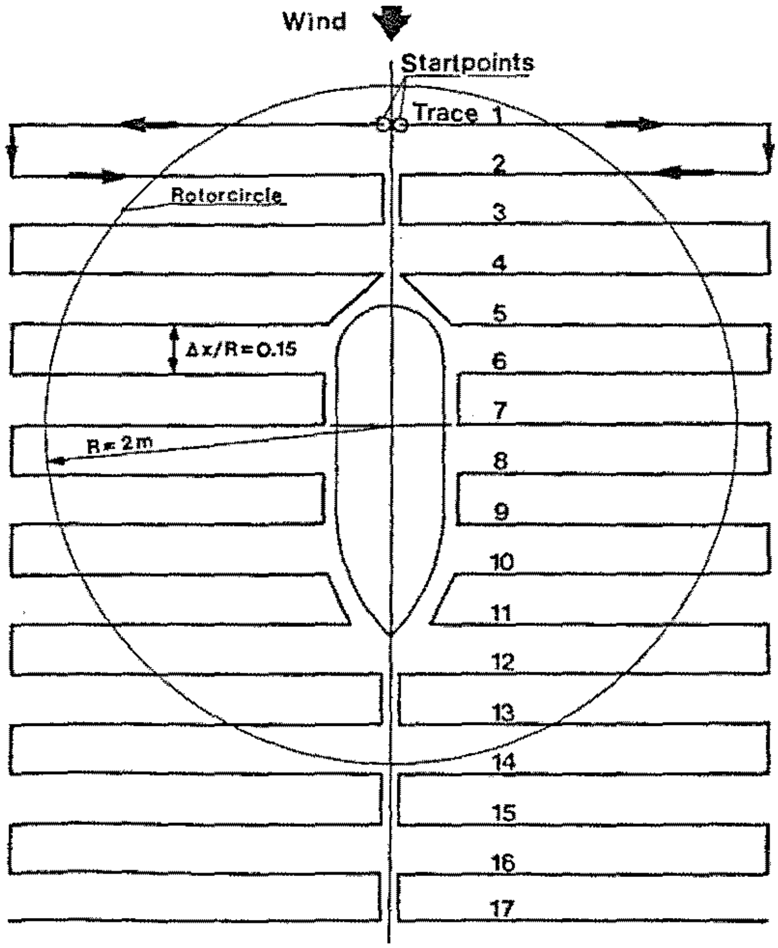

Figure 4. Traces of the probes below the rotorplane

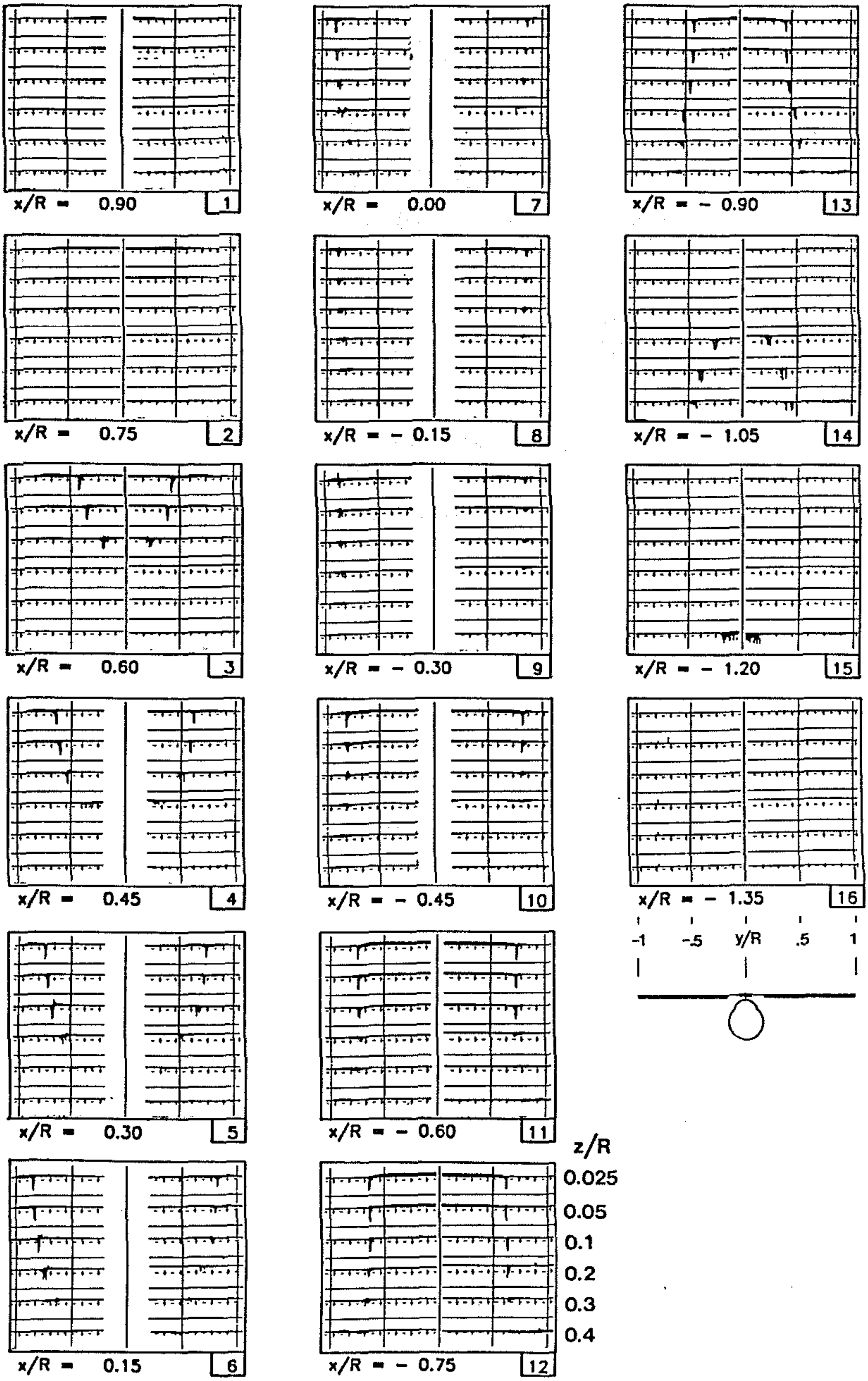

Figure 5. Pressure signals below the rotor
Transition flight condition V = 11 m/s α-Ro =-17 deg. ct = 0.0048

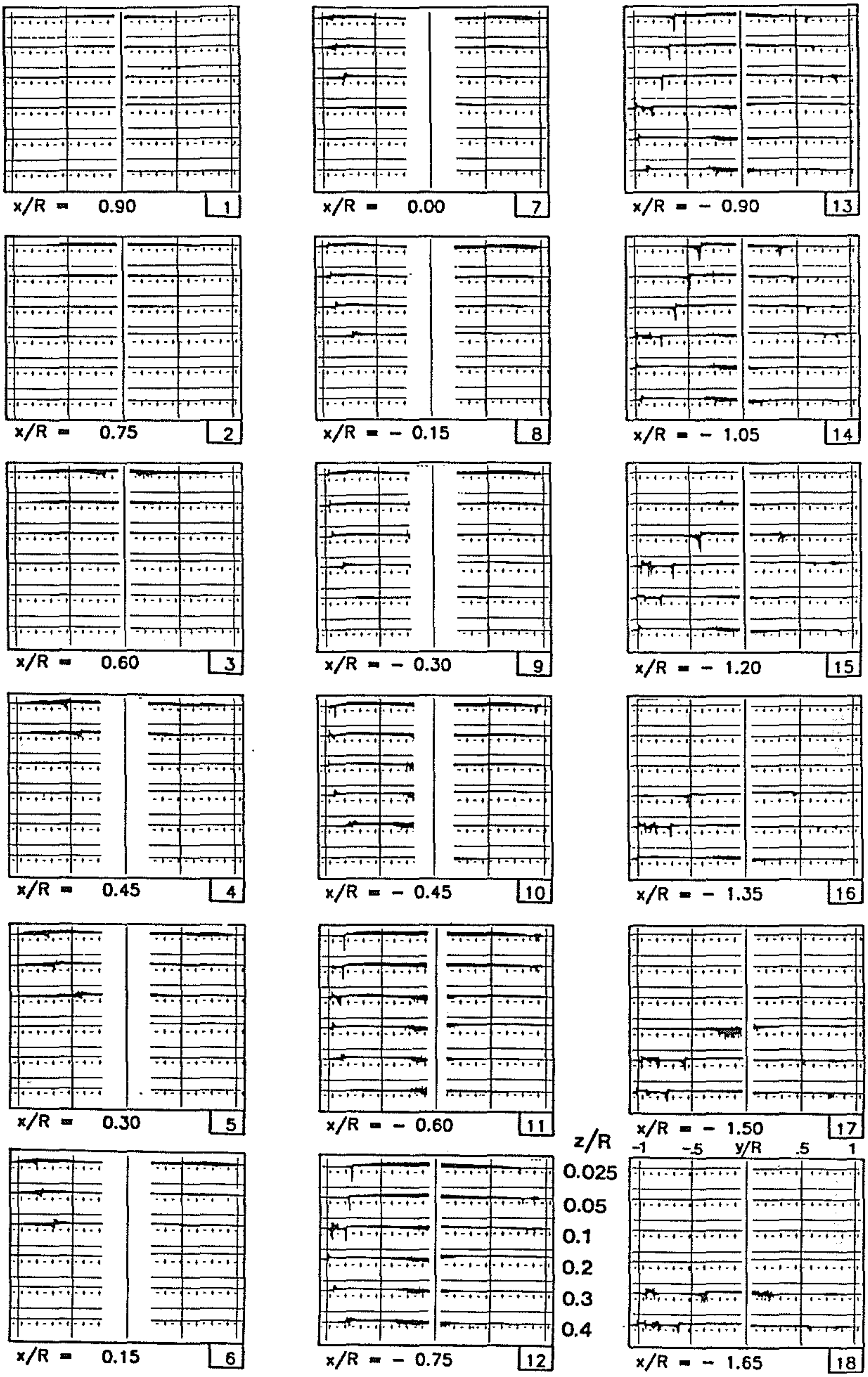

Figure 6. Pressure signals below the rotor

Climb flight condition V = 33 m/s α-Ro =-15 deg. ct = 0.0048

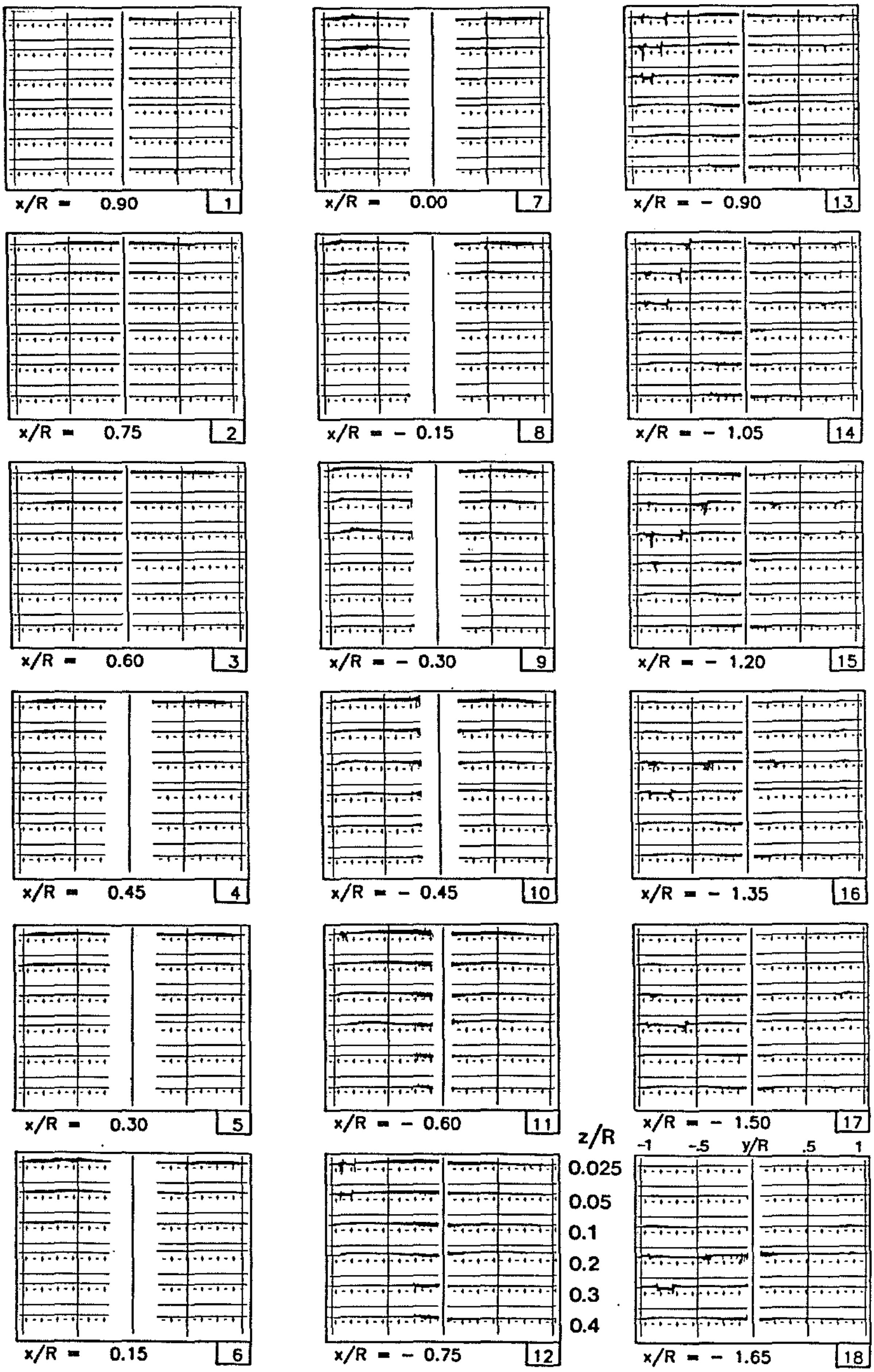

Figure 7. Pressure signals below the rotor
Level flight condition V = 33 m/s α-Ro = -8 deg. ct = 0.0048

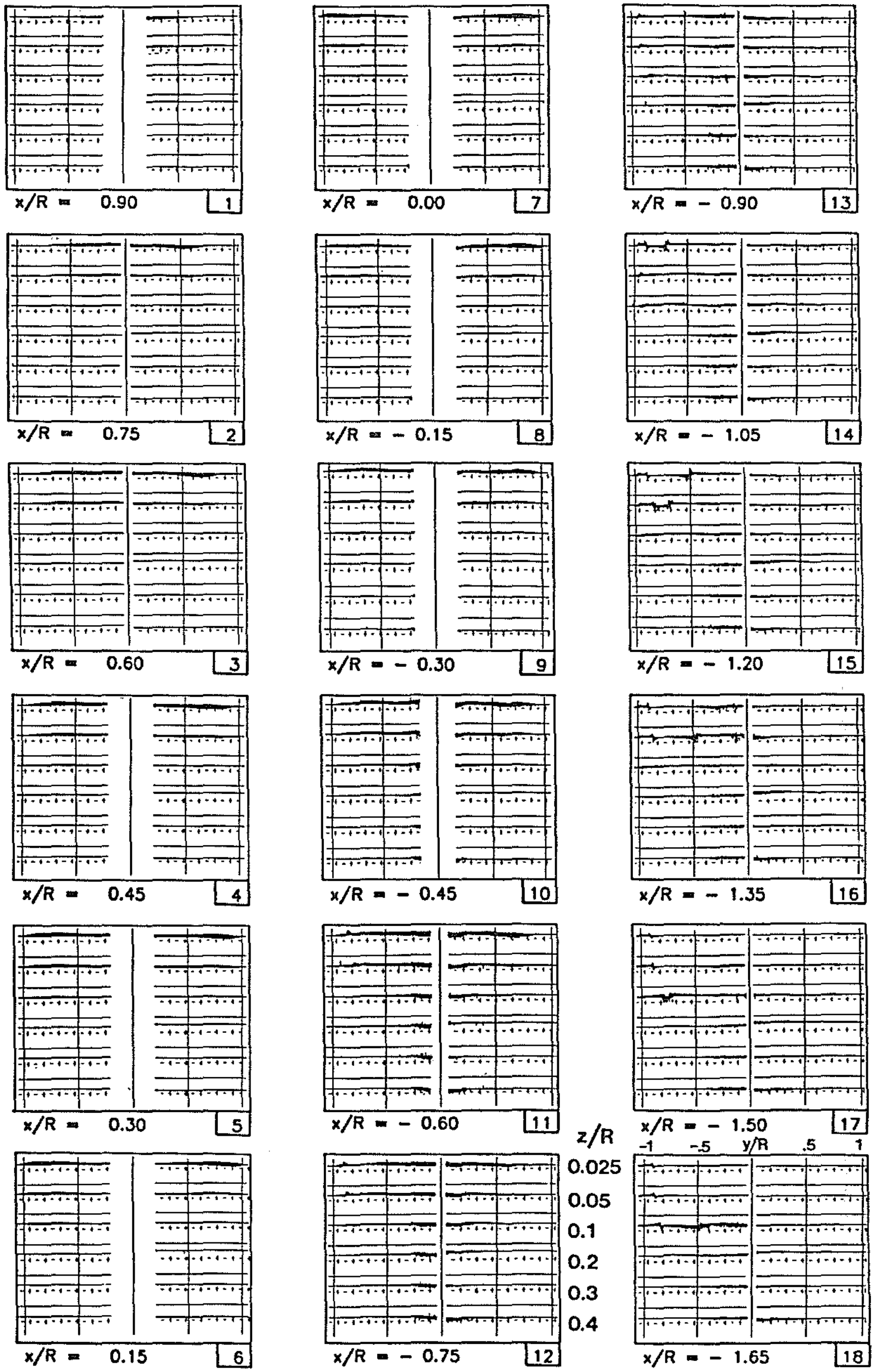

Figure 8. Pressure signals below the rotor
Descent flight condition V = 33 m/s α-Ro = 0 deg. ct = 0.0048

Figure 9. on page 20

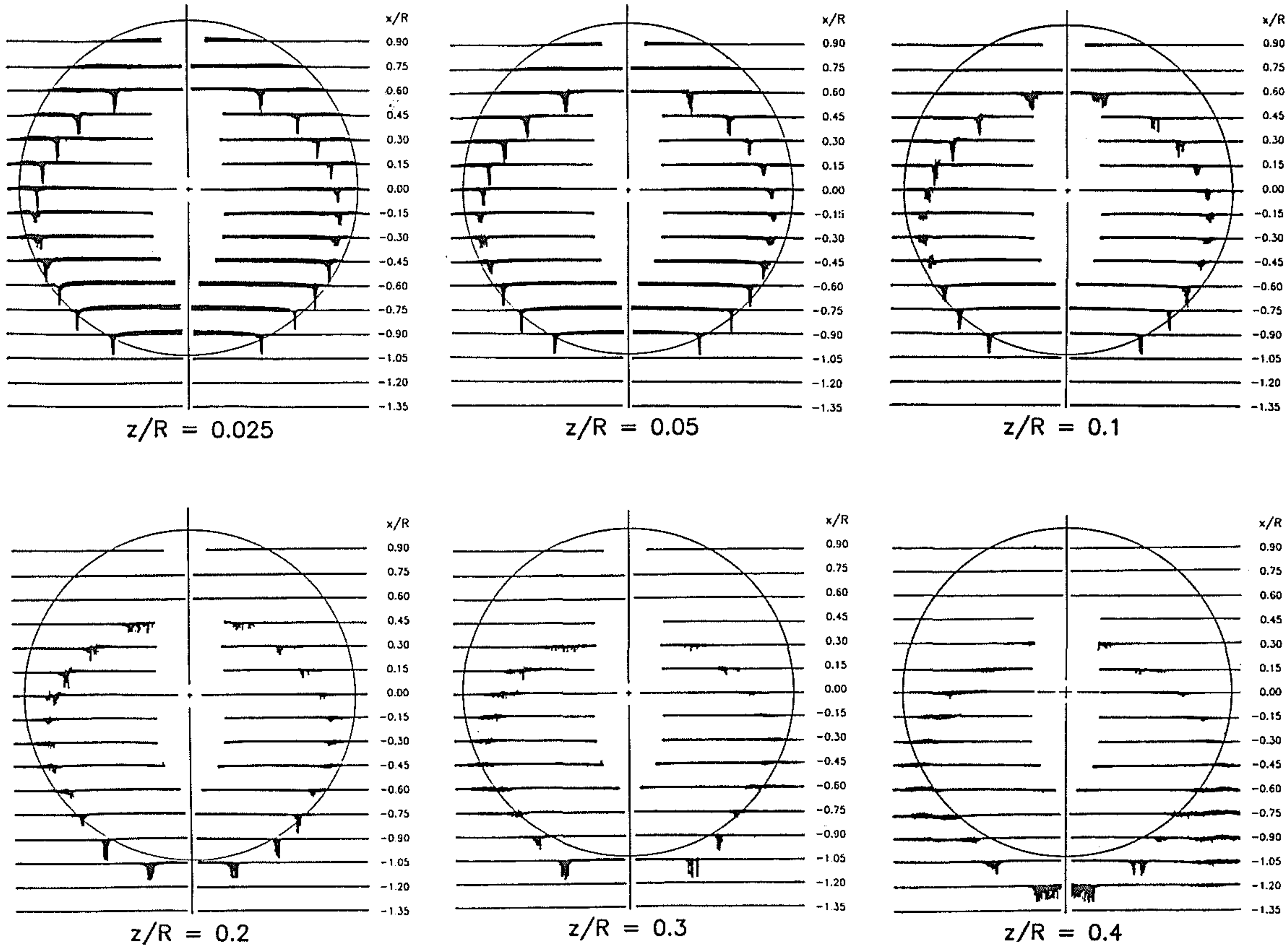

Figure 10. Vortex signals in constant z/R levels
Transition flight condition V = 11 m/s α-Ro =-17 deg. ct = 0.0048

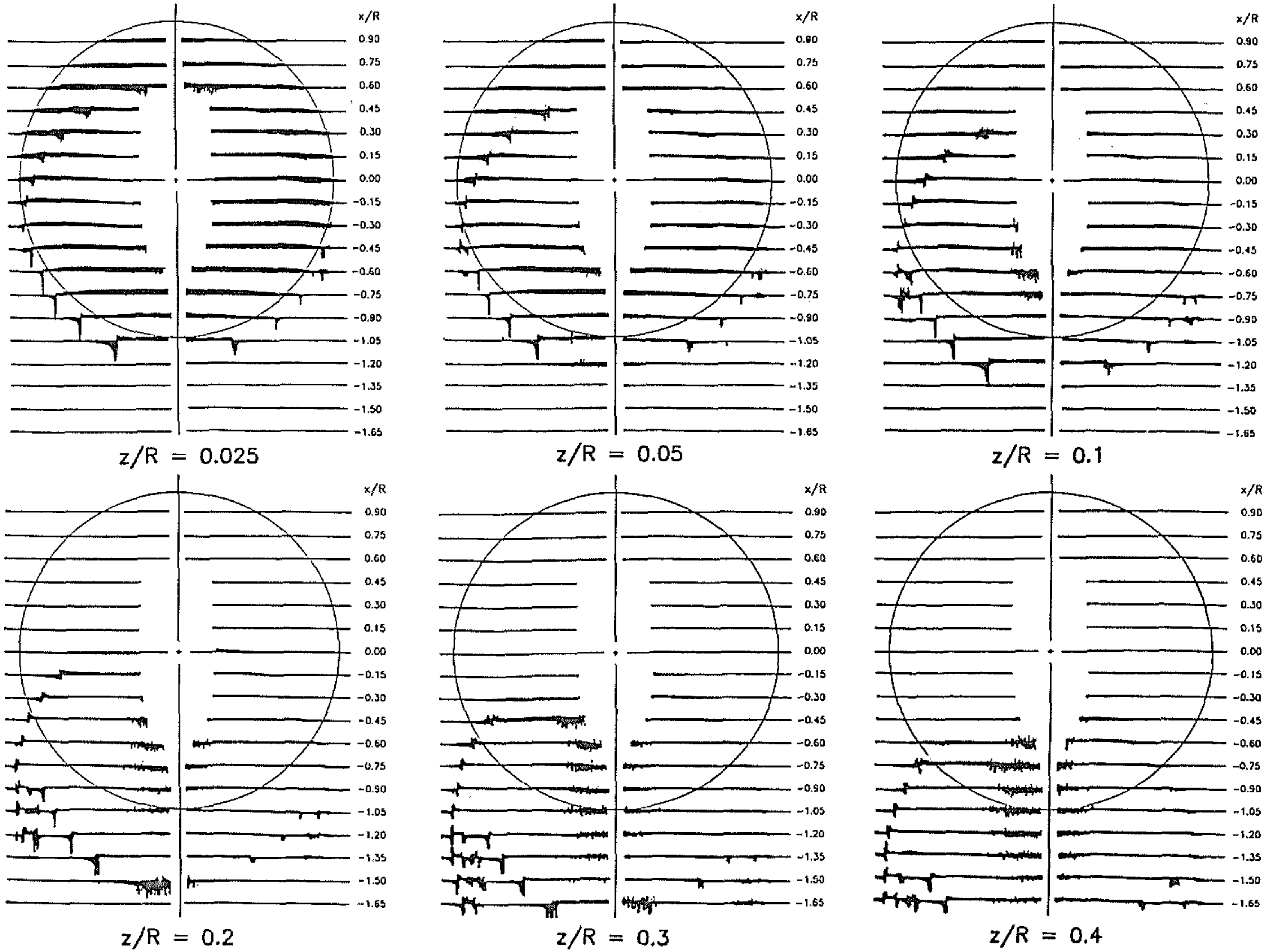

Figure 11. Vortex signals in constant z/R levels
Climb flight condition V = 33 m/s α-Ro =-15 deg. ct = 0.0048

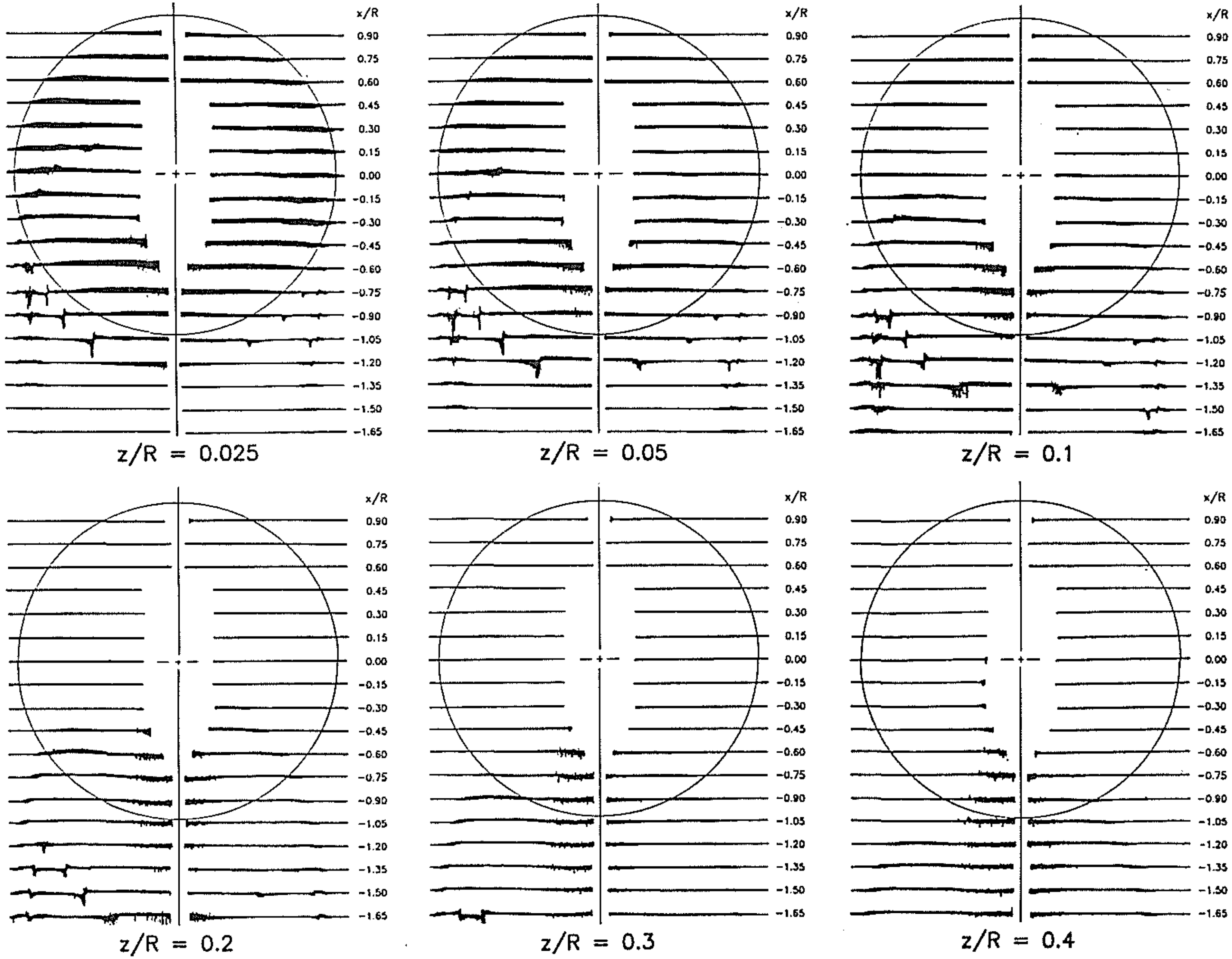

Figure 12. Vortex signals in constant z/R levels
Level flight condition V = 33 m/s α-Ro = -8 deg. ct = 0.0048

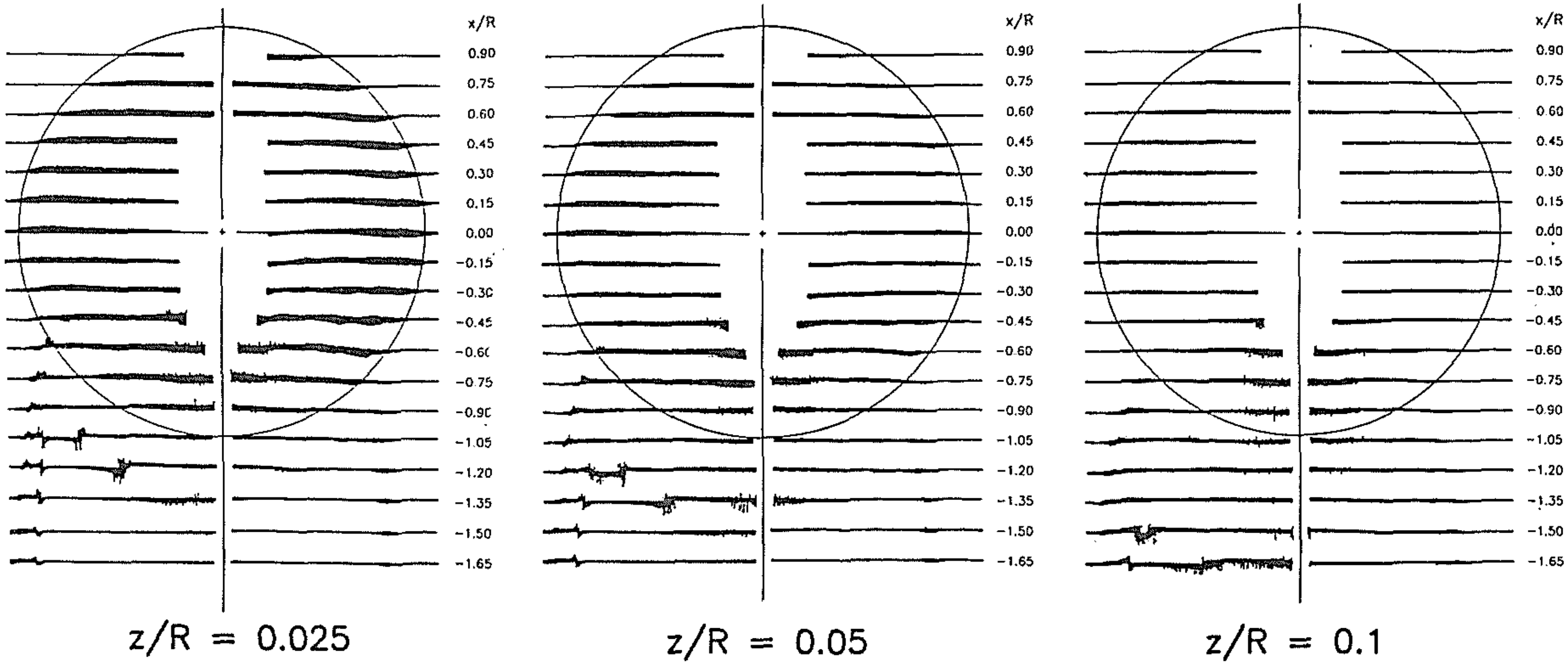

Figure 13. Vortex signals in constant z/R levels
Descent flight condition V = 33 m/s α-Ro = 0 deg. ct = 0.0048

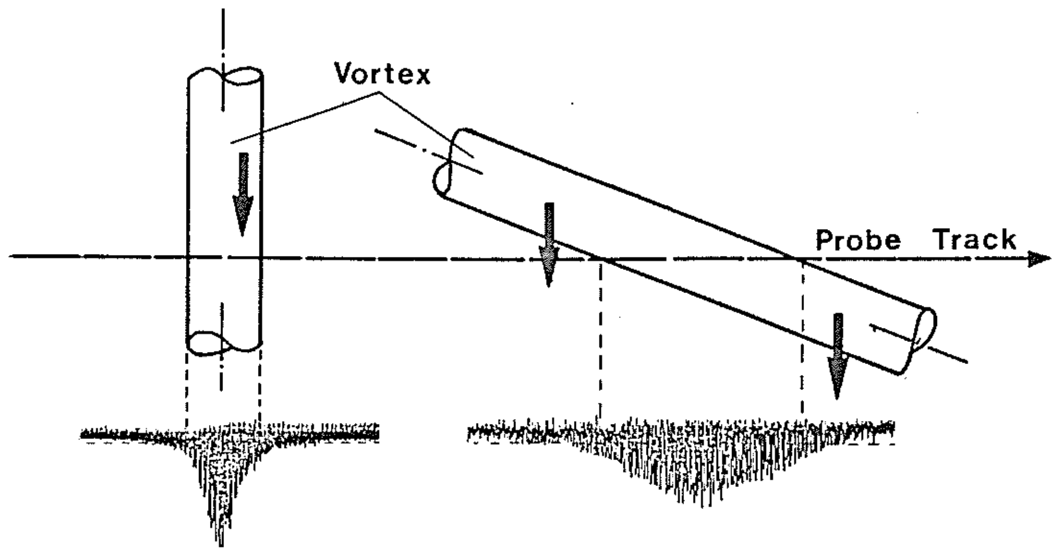

Figure 14. Different signal shapes
on the same vortex

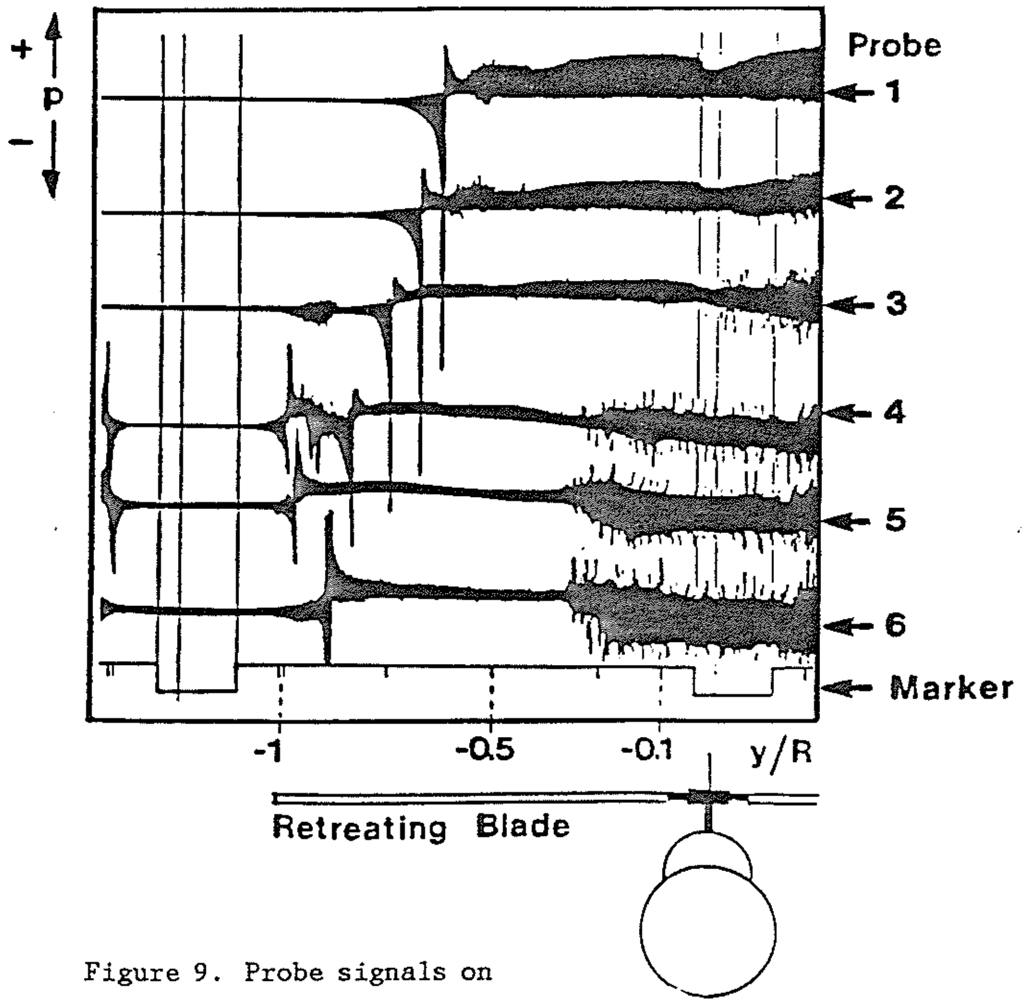

Figure 9. Probe signals on
U-V-paper strip

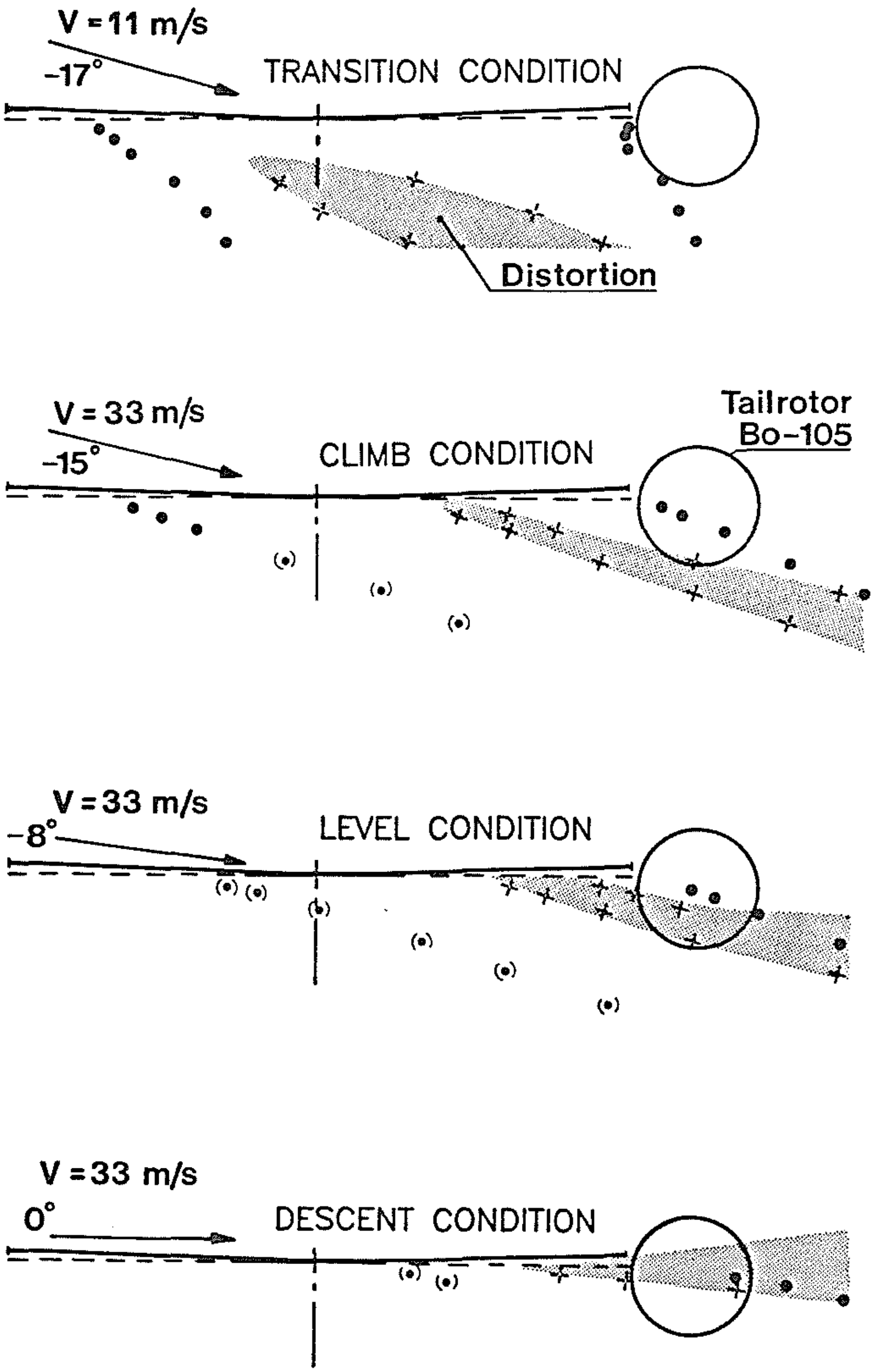

Figure 15. Different forms of downwash-cylinders

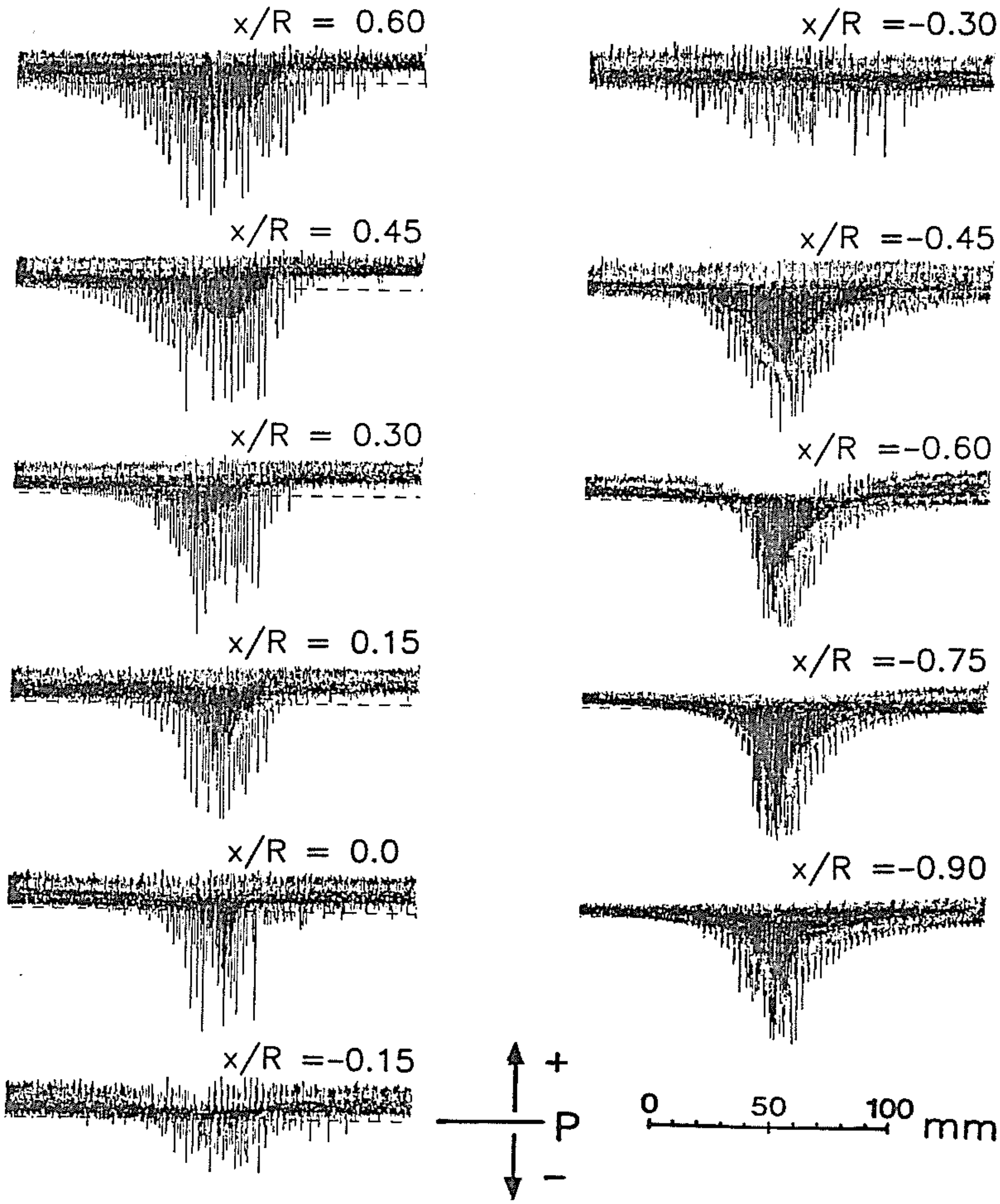

Figure 16. Vortex pressure signals in a distance of $z/R = 0.025$

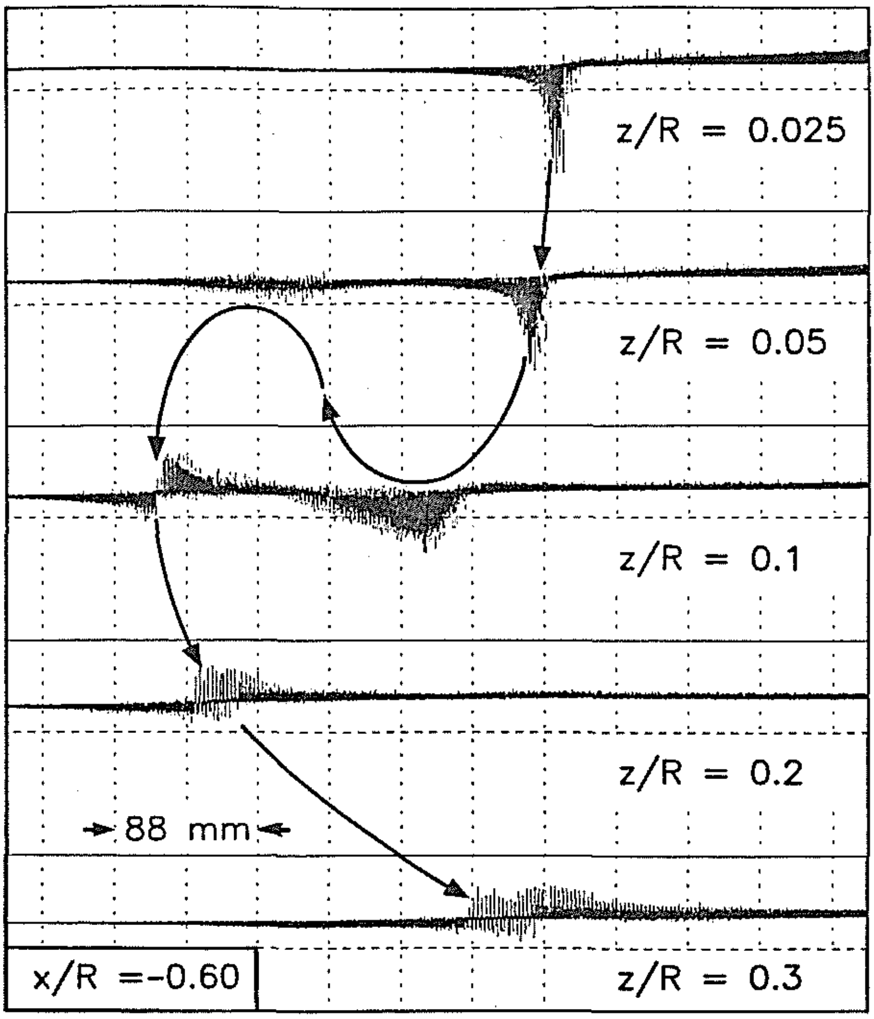

Figure 17. Trace and shape of vortex pressure signals
(Climb flight condition)

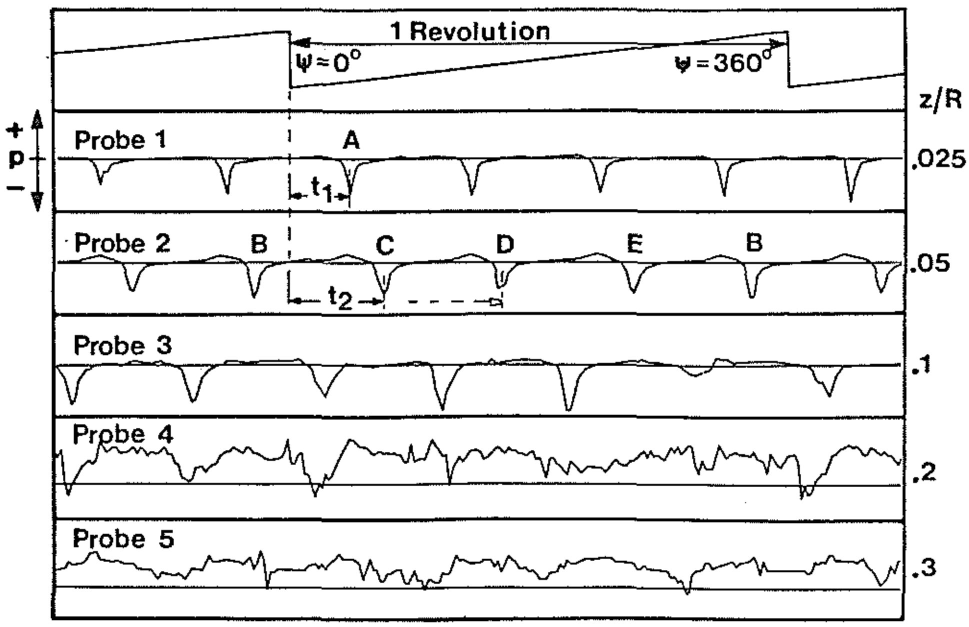

Figure 18. Expanded probe signals

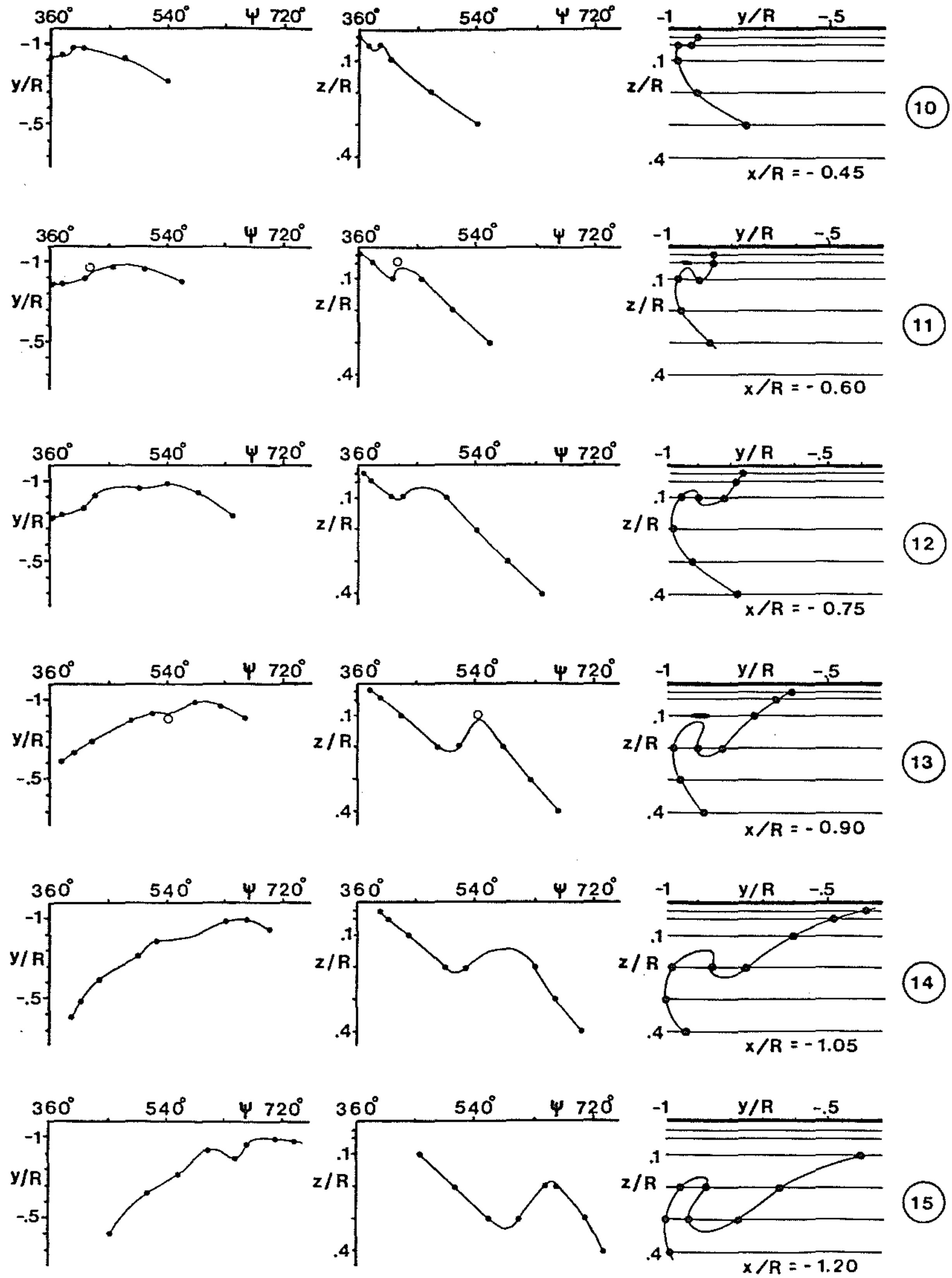

Figure 19. Time history of a vortex (Climb flight condition)