Paper No.**3**

AN EXPERIMENTAL ANALYSIS OF THE SHAPE OF
A ROTOR WAKE

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September 8 - 11, 1981

Garmisch-Partenkirchen

Federal Republic of Germany

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ABSTRACT Although the shape of a rotor wake may be described
by potential flow methods, to get reasonable calculation costs,
it is necessary to introduce some simplification in the calcula
tions. In order to check the accuracy and the validity field of
the various assumptions a set of experimental data may be a go-
od tool for comparisons. In the present paper it will be pre-
sented a hot- wire technique to detect the presence of the bla-
de wake.

Notation

S_i	Standard deviation
n	Number of samples
X_i	Measured quantity
$\bar{X}_i$	Average value of the measured quantity
Re	Reynolds Number
R_e	Rotor radius
r	Radial station
z	Distance from the blade plane
ψ	Phase angle

1) INTRODUCTION

The starting idea of this research was the need of an expe-
rimental description of the shape of a rotor wake, to support a
comparison of different numerical calculations. As we look,for
an example , at the wide survey of Landgrabe and Cheney (1),we
see a lot of different calculation tachniques, no one of them
fully exact even in the limits of incompressible potential flow
assumptions.The field of validity of the different assumptions
is not always obvious and also the accuracy of numerical results
is related to the simplifications in the method and not only to
numerical analysis problems. For this reason the comparison be-
tween numerical and experimental results on the wake geometry
seems to have great importance.

The first approach to the problem seems to be the flow visua
lization,but this shows a lack in repeatibility of results and
serious problems in the interpretation of the photographic re-
sults.This kind of techniques, that was attempted as prelimina-
ry test in the form of smoke ejection, allows a good insight
in the flow field but was not sufficient to arrive to a compari-
son. A better idea of what can be derived from smoke visualiza-
tions is shown by Bramwell (2).

Going on in the research, it was necessary to get good sta-
tistical results about the wake shape and a mean to get good da-
ta is the analysis of the turbulent structure of the wake, as it
is possible with a hot-wire anemometer. The aim of the present

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paper is to show the first results obtained in this way and to summarize the possible improvements of the measuring techniques which may be introduced observing the kind of results which were obtained.

As first, the research started with the analysis of the "steady" condition of vertical flight, in particular, simulating the hover condition, although the model was designed for forward flight conditions and for the size of the wind tunnel of the Institute.

The model , a tilt rotor, was originally designed for smoke flow visualizations, and the two blades have a stainless steel tube as spar, for ejecting smoke either from the blade tips or from the suction side of the blade at some radial station. this configuration allows also the ejection of a tracing gas as helium.

The rotor was driven by an asyncronous motor and the speed might be changed by changing the pulleys. Even if this solution is not very accurate in speed, it is reliable and very simple.

2) EXPERIMENTAL SETUP

Because this was intended as preliminary analysis for definition of the proper instrumentation and had no financial support, almost all the instrumentation was still existing and not specially adapted to the test.

The hot-wire apparatus was a standard , single channel constant temperature anemometer, connected to a digital mini-computer by a reed scanner and an integrating digital voltmeter used for strain-gauge instrumentation. This was the weakest point in the chain, because of its long conversion time. This required a sample-and-hold amplifier triggered in syncronization with the blade rotation. The syncronizing device was a photoelectric pickup of a stroboscopic apparatus: its signal was amplified and sent to a one-shot multivibrator to reshape the pulse. The photoelectric device was sensing a piece of white tape glued in different positions on the mast pulley, which was painted in black.

The hot-wire probe was mounted on a two-degree of freedom transversing mechanism, driven by DC motors contrelled by the relay card of the computer.The position of the mechanism was red by two potentiometers and sent to the digital voltmeter via the scanner. The software allowed either to place the probe in a required position or to span one of the axes or , finally, to span the whole measuring plane, which passed through the rotor axis.

All the system was monitored by a two-trace oscilloscope which could be connected either to the trigger and hot-wire signal or to the hot-wire and sampled signal. This resulted very useful to check for wire failure, for sample-and-hold droop,as would be discussed later, and for evaluating the kind of hot-wire signal. The oscilloscope was equipped with a camera and a set of pictures was taken during the tests, showing many aspects of shape of the turbulent and free-stream signal, including the strong derivatives through the vortex sheets.
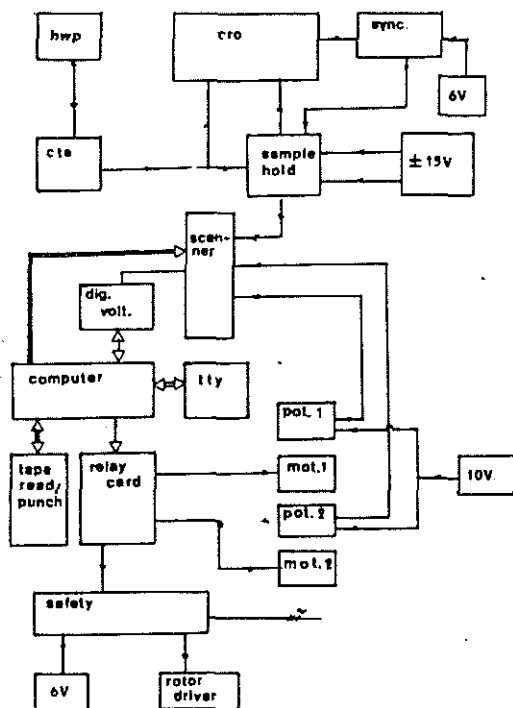
Fig. 1: Instrumentation

In order to prevent hot-wire failure, a safety system,driven by a microswitch, would stop the main motor and retract the probe through the transversing mechanism, if the probe would approach the blades too much. Another control of this kind was made by the software.

In fig. 1 the whole measuring chain is shown. Any further detail of the measuring system may be found in ref. 3.

Although very slow, the system is reliable and accurate,and was successfully used in other tests in unsteady aerodynamics, such as cyclic boundary layers, as can be seen in ref. 4. The possible modifications of the instrumentation will be discussed later.

3) ANALYSIS OF THE RESULTS

It is assumed that the wake is a turbulent one, so that, in order to find it, the standard deviation S_i of the hot-wire signal is computed, over a sample of 100 measurements.*

In this way the mean hot-wire signal is a true ensemble average and coincides with the statistical definition of turbulent mean values. If one is only interested in the wake shape, it is not necessary to pass through the hot- wire calibration curve, and even the droop of the sample-and-hold amplifier is not affecting the wake geometry. Of course, if one is interested also in the velocity values,these two things become important.

On the other hand, the oscilloscope trace has shown that the same phenomena, like the crossing of a vortex sheet, do not occurr at the same phase angle,requiring themselves a non-turbulent statistical analysis. This is the weak point of this kind of analysis , in which it is impossible to distinguish between turbulence and potential flow instabilities. In this way also the discussion of the pictures taken on the oscilloscope is either too expensive or unsignificant.

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* The standard deviation of a set of values X_i is defined as

$$S_i = \sqrt{\frac{X_i - \overline{X}_i}{n - 1}}$$

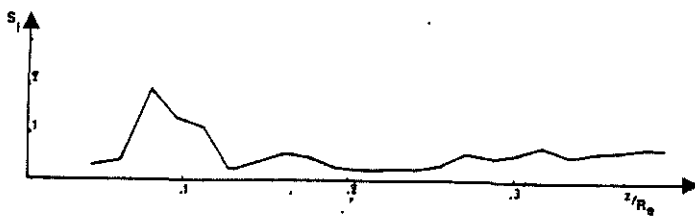if n is the number of samples and $\overline{X}_i$ their average value.

4)DISCUSSION OF THE RESULTS

Fig. 2 :Standard deviation versus axial distance. r/R_e = .73 ψ= 60°

The standard deviation of the hot-wire signal is plotted versus the axial distance from the blade plane, as shown in fig.2. This is a typical plot, showing a peak across the wake at a certain phase and for a certain radial station. It can be seen that the curve is not smooth , due to the limited number of samples. This is a first result of this kind of statystical analysis and any attempt of performing such a statistical method will require a quite larger computer.

Fig. 3 Standard deviation versus axial distance ψ=90°

A second way to present the data is to compare different types of these plottings, for the same phase angle and for various radial positions, as shown in fig. 3

In this way it is possible to represent the pitch angle of the wake, which is similar to a straight line,according to the fact that the model blades are untwisted.

Near the blade tip it is possible to observe a large peak, due to the strong tip vortex. The two smaller peaks close to it may represent the roll-up of the vortex sheet, but there is no proof of it up to now.

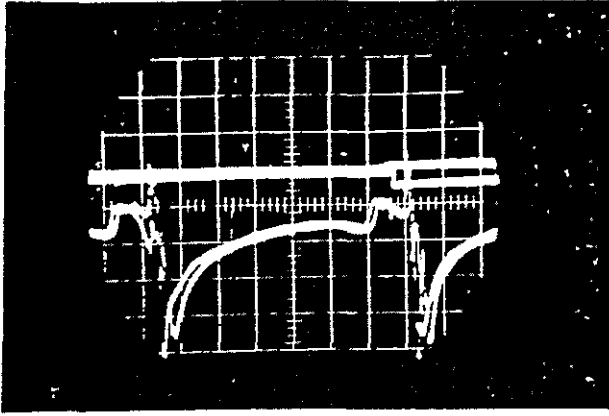Another result is that an extrapolation of the wake up to z=0 does not give ψ=0,but a little negative value.This is a dissipative "displacement" effect which will not be predicted by potential flow theory and is due to the fact that, immediately behind the blade,the wake has little velocity relative to the blade and has only induced velocity. It is analogous to the displacement thickness in boundary layer-outstream interaction.

Another possible source of information is the set of pictures taken on the oscilloscope. An example is shown in fig. 4 to 8.

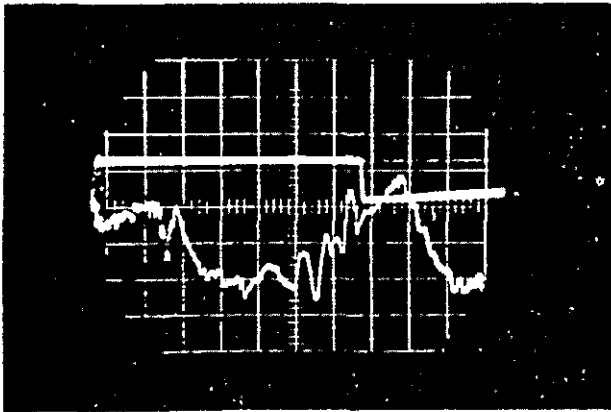Fig4- r/R. - 0.82 ; z - 17 mm. , ψ 0°
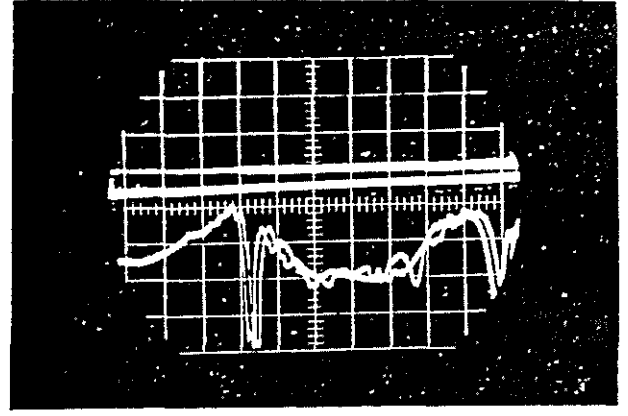
Fig. 5 - r/R. - 0.87 ; z - 147 mm/ ; ψ : 0°

Fig.6- r/R. - 0.82 ; z - 230 mm. ; ψ : 0°

In fig. 4 and 7 it is possible to see the crossing of a vortex sheet as a high velocity gradient, shown by the lower traces, which represent two revolutions. (The upper, stepping trace represents the sampled signal and shows a remarkable droop). Fig. 5, for example, shows a peak which is not understandable as a vorticity component normal to the probe wire. This suggested that a fully three component hot-wire probe be will be needed for a statistical analysis, at least in the part of the roll-up of the vortex sheet. In this sense a set of 3-D probes is actually under calibration for going on in the tests.

As said before, the peaks in the hot-wire signal do not coincide in phase angle, and this might be explained either by ambient
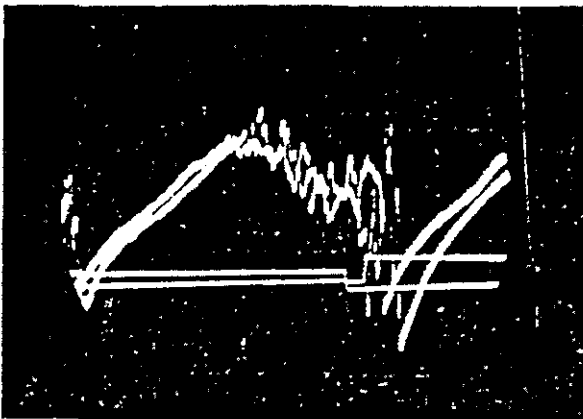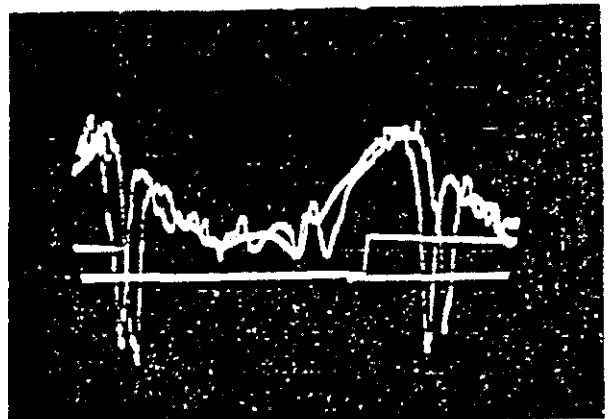

Fig.7 - r/R. - 0.87 ; z - 13 mm.; ψ : 180°

Fig.8 - r/R. - 0.87 ; z - 95 mm.; ψ : 180°

turbulence or by vortex"wandering"as consequence of potential flow or interaction instabilities. In the latter case, a statistical analysis of the phenomenon would be very interesting, because the same would occurr as calculation instability in numerical methods.

The present instrumentation and analysis thecnique do not allow such evaluation, so that, in coincidence with the development of new hot-wire probes and instrumentation, a new data acquisition system is under development, as discussed now.

5) FUTURE DEVELOPMENTS

Although the actual test has shown the feasibility of a statistical rotor wake analysis, it has also shown the way of improving the measuring technique. As first, it is important to be able to record the whole cycle, to detect where the vortex sheet crossing occurs, in order to build up histograms of the wake shape and not average position of the wake.In fact, if one looks to the curves of fig. 3 and to the pictures, he can notice thet peaks in the pictures are much sharper. This leads to the idea that a correlation not only on the phase angle but also on the peaks will give a more accurate definition of the shape.

In this sense,accurate integrating digital voltmeters should not be used, but it would be better to use fast 8 or 12 bit successive approximation analog to digital converters. Direct memory accessing will provide syncronization of measurements to the phase angle. 8 bit accuracy seems to be enough, this allowing fast conversion and large memory capability. A 32 K 8 bit memory is compatible with most microprocessors and will allow a storage of some 300 samples each degree of phase for a 3-component hot-wire anemometer,giving reasonable data for each wake point and experimental times 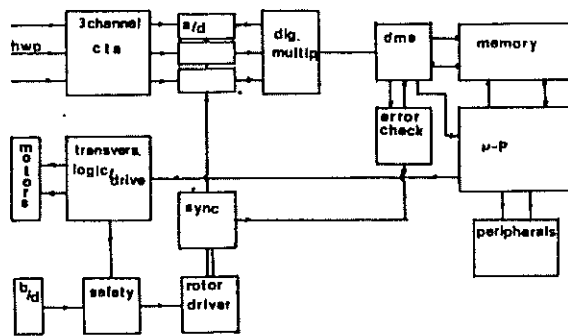not comparable to months as the actual instrumentation does.A scheme of the instrumentation which is actually under development is shown in fig. 9.

To save conversion time the signal of the triple hot-wire constant temperature anemometer is multiplexed digitally after conversion.(3-sta te output A/D converters allow very easy multiplexing).

Fig. 9 New instrumentation

To allow a closer approach to the blades,the blade detection will be photoelectric instead of mechanical,in order to reduce also the inter-

ference,by means of optical guides. Of course, the very high speed of data acquisition of this new instrumentation is not a requirement of rotor model testing, but is necessary for other tests, as propellers and other unsteady phenomena.

Last comment is the ability of handling data of a limited number of samples. Instead of increasing the quantity of measured data it should be better to use interpolation functions such as theoretical wake velocity profiles and to search maxima by least squares thecniques.

6) CONCLUSIONS

Although limited by financial problems, this preliminary analysis gave good information about the quality of the obtainable results and indications how to improve this measuring techinque. In this sense , the true research is now starting, and the new electronics are designed and under testing. A new three-channel hot-wire anemometer was bought and the old one will detect free-ambient turbulence. In this way it might be possible to correlate vortex sheet "wandering" to ambient conditions, if a correlation does exist,because the problem of discriminating between turbulence and potential flow instability is still open.

The requirement of three-component velocity measurements will suggest to go on with hot-wire anemometry instead of trying laser doppler systems , due to the problems connected with three dimensional laser measurements.

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