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THREE COMPONENT HOT-WIRE MEASUREMENTS IN THE WAKE OF A ROTOR MODEL

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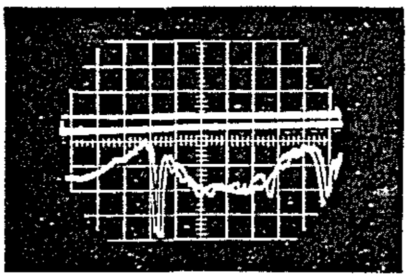
ABSTRACT

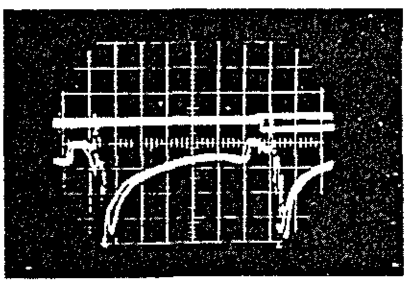
According to previous experience in hot-wire measurements in the flowfield of a rotor model in hover conditions, the paper describes problems connected to this kind of experiments and their possible solutions.

In particular, it deals with the reliability of directional measurements related to triple hot-wire probes, the data validation procedure and validity of experimental results, the choice of probe orientation and some uesful way of presenting the results in graphical form.

Furthermore, the paper discusses one way to analize the signal in statistical form in order to reconstruct turbulent or vertical structures without the usual "smoothing"associated to ensemble averages due to the long-period "wandering" of the wake.



A) $r/R_0 = .87$ Z = 147 mm Phase = 0°



B) $r/R_0 = .82$ Z = 17 mm Phase = 0°

FIGURE 1 Signals of a single hot wire probe in the rotor flow.
Is the peak in figure A) a vortex sheet or a prong wake? In figure B) the peak shows a typical velocity discontinuity produced by a vortex sheet.

INTRODUCTION

The measurements of the rotor wake are wide problems in which we may recognize the following main aspects:

-the overall induced velocity field,
-the shape of the shed vortex sheet,
-the structure of tip vortices,
-the interference between wakes and blades, the unstesdy effects on the structure.

It is usually impossible to obtain information about all these phenomena in a single experiment or by a single measuring tachnique. For this reason it is quite interesting to investigate the limits of possible applications of hot-wire anemometry to the wake analysis. As preliminary work, it is interesting to discuss briefly the reasons to use single, double or triple hot-wire probes and to compare them to laser anemometry.

The rotor flowfield is largely unsteady in the sense that, mainly in the tip vortices, not only the velocity value but also its direction change in time with very steep gradients . A second remark is that the flow is not periodic but contains two kinds of almost random fluctuations: the first is short-period and may be recognized as turbulence, while the second has a time scale quite larger than the rotor revolution and may be produced either by environamental turbulence or by potential flow instabilities (or by both?). On this basis we can assume that the hot-wire applications are limited by the directional response of probes, which does not affect laser anemometry. But the cost of laser system is also a relevant problem. On the other hand, the theoretical or empirical bias correction in laser anemometry is still an open problem, the seeding of large flowfields is not so easy and, finally, seeding particles may not fill the vortex core.

The number of wires is a second important question. From the authors' experience it seems that, in many cases, the time response of a probe to the crossing of a thin vortex sheet is rather similar to the response of a wire when it is sensing the wake of one of its own prongs: in figure 1-A it is possible to see a peak which origin is not clear. (from ref. 1). In this sense, the use of single or double wire probe is limited by the skillness in detecting correctly similar phenomena. On the other hand, in any double or triple wire probe the number of prongs is larger, giving more interference probability,and it is also possible to have thermal wakes and another interference effect.

1) 3-D MEASUREMENTS AND DATA ACQUISITION

Three-dimensional measurements are rather difficult in any kind of tests, even with pressure probes. Of course, they are also difficult with hot-wires, mainly due to interference and probe volume , but also for the fact that the velocity sign is not recognized. In this sense laser anemometry has some advantages, although it is difficult to measure three orthogonal components. Also data acquisition may be a problem with many commercial systems. If one wants to know the correct history of the velocity field for statistical data analysis, he shall measure many points in the same revolution, (at least each 2°) for measuring the steep gradients in the vortex sheets. Furthermore, for a correct discrimination between harmonic and subharmonic frequencies, it is necessary to measure many revolutions (at least,10).

The three components of the hot-wire signal should be measured at the same time and not one after another, to avoid systematic errors.

Finally, we should note that, to keep constant the tip Mach number, in any model test, the angular speed has to be increased with respect to full-scale. Therefore all frequencies are larger requiring shorter data acquisition times.

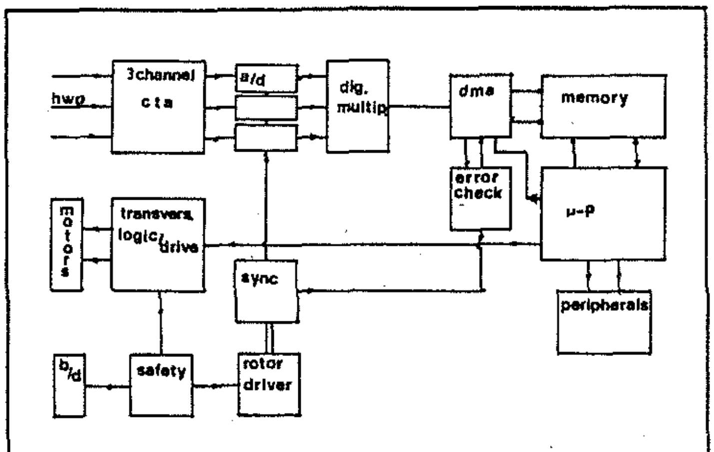


FIGURE 2 The data acquisition system

All those things led to the requirements for a data acquisition system which was specifically designed for this task.It was yet outlined in a previous paper presentad in one of these forums (1) and is described in details in another paper, (2).

The principles of the system, sketched in fig 2, are simultaneous data acquisition and analog-to-digital conversion with external triggering: it allows measurements at prescribed azimuth angles. Successive digital multiplexing and direct memory access are syncronized to the computer clock.

The system results therefore cheap and reliable and gave no measurement problems. In actual form it allows measurements up to a frequency of 30 kHz and has 32 K of direct accessible storage, plus some 16K for programs and data handling.

2) MODEL AND EXPERIMENTAL SETUP

The tests reported in this paper are relative to our two-blade tilt rotor model, yet described in (1). The rotor diameter is 1.16 m, the blade chord 55 mm, the angular speed 1000 rpm.

The instrumentation consists in a three channel hot-wire system, a triple probe with the wires aligned in axial, radial and tangential directions, a photoelectric device giving probe proximity signals in the range within the two last millimeters from the blade (safety system) and the data acquisition microcomputer as described in the previous paragraph. A drilled disk is mounted on the rotor shaft and has a reference hole and 256 equally spaced holes shutting the light of two photoelectric sensors. A modulo-256 counter produces the encoding signal and an error detector checks if the counter is at zero setting when the reference hole is crossed.

The counter output,used as address for direct memory access, is also converted in analog form and sent as X-axis signal to a four-traces oscilloscope to present the three wires signal and the safety signal both for monitoring the whole test and to look at the signal aspects. Significant pictures of the screen were taken and one is shown in the paper as fig.8.

3) TRANSFER CURVES AND DATA VALIDATION

A hot-wire is equally sensitive to any velocity normal to it, thus it does not feel the velocity sign. Furthermore its response to the velocity modulus (scalar response) is not linear and its sensitivity tends to zero as the velocity tends to zero also. For these reasons it is difficult to obtain accurate information in a fully unknown flowfield. If high accuracy is not required, (let's say some percent of error) it may be assumed that the directional response in a plane containig the wire is sinusoidal. In the ± 50° range a good probe may have errors less than 2%, as shown in fig. 3. This transfer curve is not correct only for very low velocities, when thermal convection dominates, but it is possible to avoid operation in this regime, at least reducing the probe overheath ratio in order to decrease the self-induced convective flowfield. This is a typical problem only for small models of reduced power and will be negligible in full-scale tests.

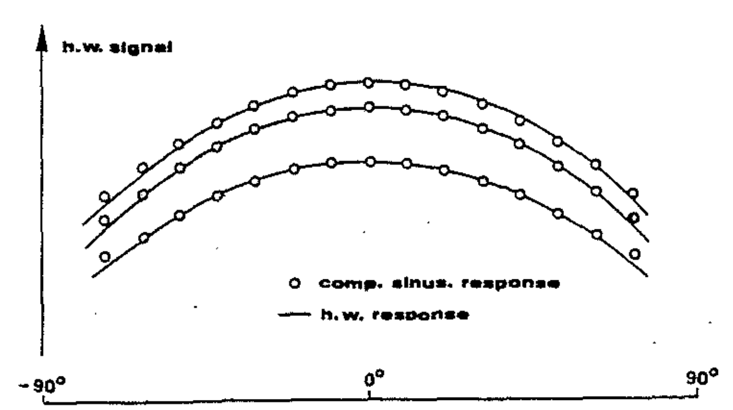


FIGURE 3 The directional response of a single hot wire probe at various flow velocities, compared to a sinusoidal response.

In this case, for three equal orthogonal probes, the ratio of the signals is proportional to the direction cosines of the velocity vector,thus its resolution, both in direction and modulus is rather simple. If better accuracy is desirable, an iterative procedure outlined later on will give good results.

Unfortunately, for a multi-wire probe the response is much more complicated and it may not be even monothonic, for the interference effects, as shown, for example, in fig. 4. The figure represents the directional response of the three signals of a probe rotated around one of his wires in an uniform flowfield. In principle, the calibration would be correct at least in a half sphere, but, at large angles, strong deviations

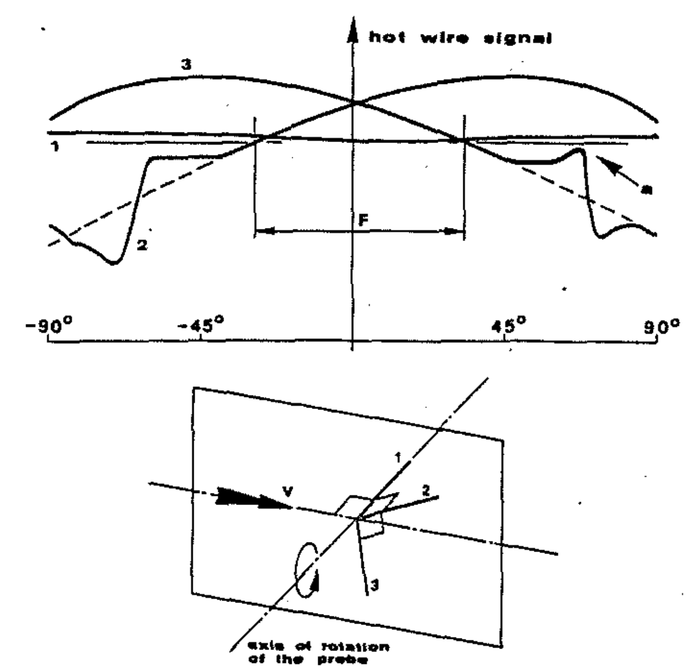


FIGURE 4 Directional response of a triple hot wire probe with wire 1 normal to the flow direction and rotated as shown in the lower sketch. The arrow "a" indicates a necessary safety margin.

show interference effects, produced either by the prongs or by the thermal wakes.

Of course, the problem is to detect, from the measured signal, when the flow direction is such to produce unreliable data. Otherwise the test would be meaningless at all. It is therefore necessary to establish some automatic data validation procedure either during acquisition or during data reduction programs. Not valid data have to be rejected and the experimenter must be informed of data rejection in order to decide whether:

- change the probe orientation and repeat the test, if the scatter of data is not too large,
- try to obtain some information from valid data only, if the scatter is very large.

The term "large scatter" means here that the flow direction fluctuates in a cone larger than the one in which the probe can be uniquely calibrated. A test like the one of fig. 4, repeated around all wires, will define this cone. We shall not only limit the angle in the range of sinusoidal response, but also the signal shall never be larger than the spurious peaks that may exist in the probe response, as it appears at the right hand in fig. 4. This may be a much more limiting condition as can be seen on the figure, where limiting angle is shown, with a small safety margin. The smallest of the possible angles, referred to the probe axis and not, as in the calibration procedure, to the axis of rotation, gives the safe operation cone.

When the limiting cone is known, we can establish the validation procedure:

1) if the wires are not exactly equal, we must correct their response, in order to have the same signal for the same velocity: it is only a multiplicative constant;

2) from the three corrected signals, s , r , and t we obtain the modulus m as:

$$m^2 = r^2 + s^2 + t^2 \quad ;$$

3) we get the direction cosines , a , b , and c as:

$$a = r/m \quad , \qquad b = s/m \quad , \qquad c = t/m$$

and the direction of the velocity vector with respect to the probe axis;

4) we compare the direction with the limit cone and decide wether accept the data or to reject them;

5) from the modulus m, throughout the scalar calibration curve, we get the velocity modulus.

We need therefore three triple directional calibration curves and a single scalar calibration, aligning the probe axis to the flow.

For taking into account that the response is not exactly sinusoidal, after having calculated the first approximation velocity vector, it is possible to reevaluate it on the basis of the calibration curves instead of the sinusoidal laws.

4) PROBE ORIENTATION

As formerly seen, the probe should be oriented to the velocity vetor within the correct cone, in order to have reliable data. It is therefore desirable to know a priori the possible orientation of the velocity vector.

On the other hand, it is also desirable, whenever possible, to choose simple and conventional orientations, like axial, radial and tangential with respect to the rotor axis.

We may now observe that, in hover or vertical flight conditions:

-the tangential velocity is directed in the sense of rotation both upstream the blade (for the presence of a stagnation point) and in its wake, for the kinetic energy loss. In between, for the effects of thickness and circulation, it has opposite direction on the upper surface and also on the lower surface for small lift coefficients, as sketched in fig. 5a;

-the axial velocity is directed downwards, except in a limited region close to the tip vortices and possibly upstream the blade lifting vortex (upwash), as shown in fig. 5b;

-the radial velocity is always directed inwards, except in the case of ground effect as shown in fig. 5 d and e.

As far as the blade tip region is concerned, it should be noted from the classical actuator disk theory that the stream tube must be tangent to the disk, thus giving no mean axial velocity at the blade tips. This is the only way to obtain continuous pressure at the tips: otherwise the points P1 and P2 in fig. 5c shoud have different pressures, although equal to pressure in P3. On the other hand it is well known that a blade impinges the tip vortex of the preceding one.

In this tip region there is the maximum change in the direction of the velocity vector, because one component has no mean value and therefore its flow is the

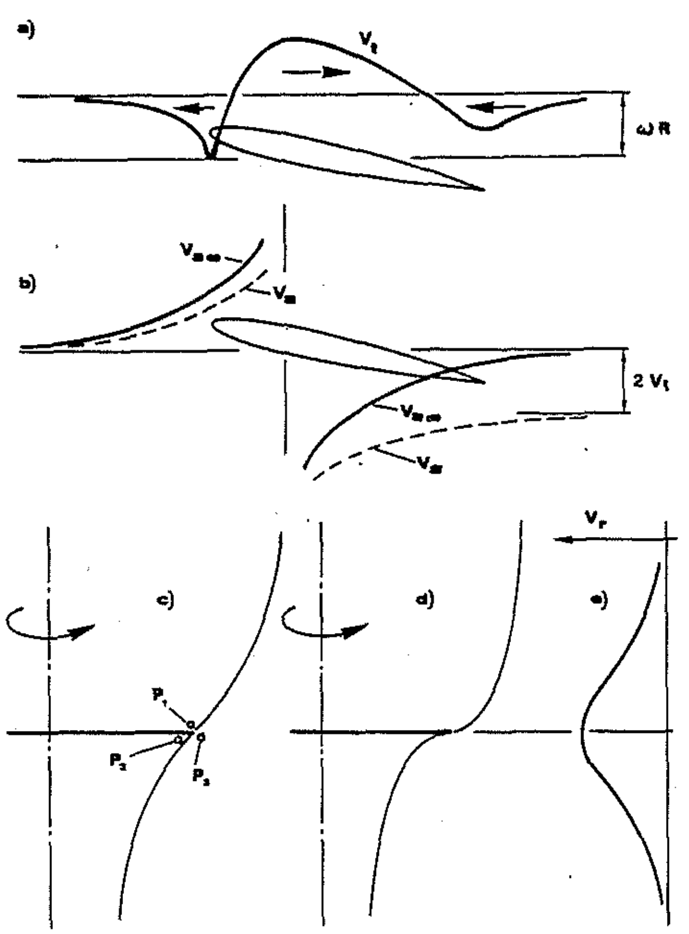


FIGURE 5 Details of the rotor flowfield

a) The tangential velocity V_t induced by a blade. Arrows indicate the flow direction with respect to the probe.
b) Axial velocity induced by a lifting vortex: $V_{a\infty}$ in two dimensions, V_a in the rotor flowfield.
c) d) Details of the rotor stream tube.
e) The radial velocity induced by the rotor.

most difficult to be studied with a single probe orientation. Furthermore, the tip vortex lays in the field sweeped by the blades and it is impossible to go into it with any fixed device, and therefore also with fixed hot-wires.

This region must be therefore analyzed either by flying hot-wires or by laser anemometry.

For axisymmetric flows, it appears that the best choice is to have effectively three wires oriented in axial, tangential and radial directions, with the probe support directed downwards, inwards and against the rotation. It is impossible to direct the probe support upwards to measure the flow close to the blades, when we may find upwash, for geometrical interference, so that some special probe may be useful.

The problem would be much more complicated in forward flight simulation, where the probe axis should be gradually oriented against the onset flow. Actually we did not test similar configurations.

5) DATA PRESENTATION

It is quite obvious that the data presentation in table form is rather impossible to understand, as the number of data increases, as in a complete flowfield.

On contrary, graphic presentation is reasonable whenever several (but not too many!) data have to be presented on the same sheet.

A perspective three-dimensional view of the velocity vector, represented on a plane sheet of paper, is, in our experience, rather difficult to look. Therefore, on a graph, it seems to be better to represent in vector form two of the three components in one plane and the third component separately. Two seem to be the most useful representations:

- the first, suitable for the velocity field in planes normal to the rotor axis, the velocity is divided into the vector parallel to the disk and its normal component and then projected from a suitable view angle;
- the second, suitable for the development of vortex sheets, the velocty vector is divided in its component normal to meridional plane and the vector in that plane.

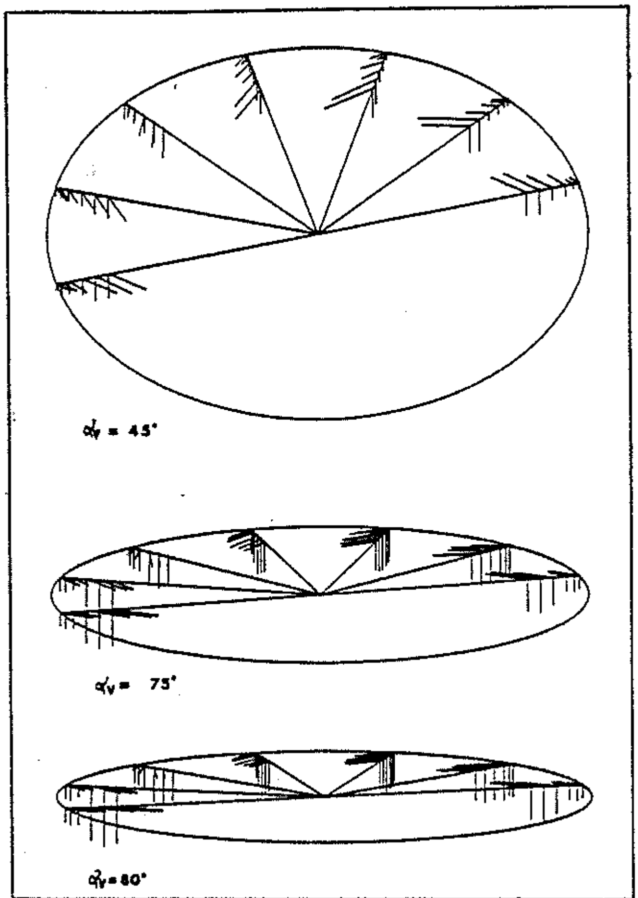


FIGURE 6 Various angles of view for the graphic representation of the plane vector and the axial component of the three wire probe signals.

The first one was tested, as the second is more familiar, and the view angle was changed in order to obtain the most understandable graphs (figures 6 and 7). In figure 7, with an angle of view of 60°, the sudden changes in the velocity field due to the presence of vortical sheets is clearly visualized by the strong deviations of the hot wire signal vectors in a plane parallel to the rotor disk.

It must be noted that, although data were obtained at 256 azimuthal positions per revolution, only points spaced of 30° are reported for simplicity, in order to get an intelligible representation.

When the small scale structures of the signal are particularly interesting, it would be better to present the hot-wire signal as a function of azimuth at each measuring point, as shown in the oscilloscope picture of figure 8.

6) DATA ANALYSIS

During the acquisition of instrumental measurements or of statistical data, the unavoidable inaccuracy of methods and instruments or the randomness of sampling introduce some deviation from original values.

To overcome such devia-

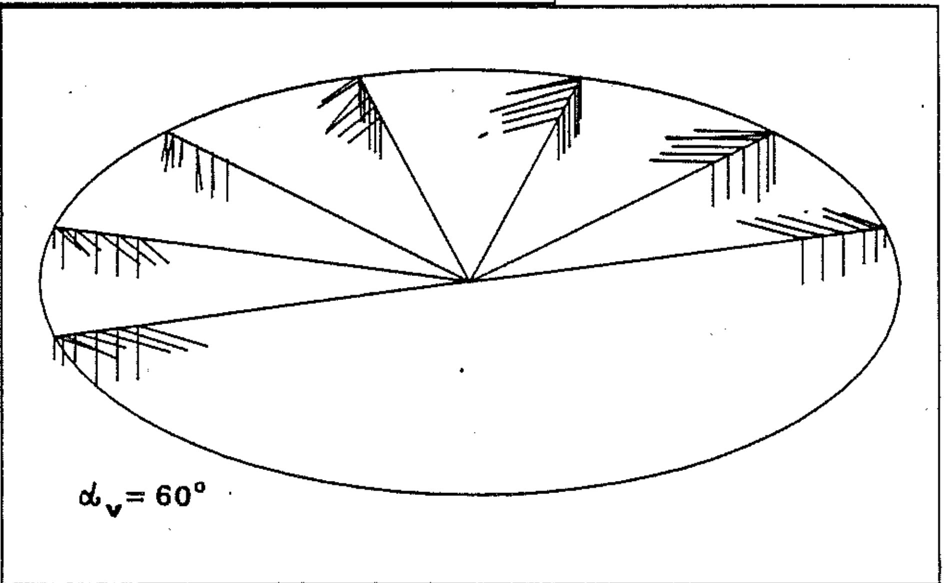


FIGURE 7 Graphic representation of the hot wire signals showing the crossing of vectors in the vortical sheet (angle of view = 60 degrees).

tions and to obtain a better interpretation of the phenomena, suitable correction methods can be used.

In the particular case of repetitive phenomena, which obviously have a periodic behaviour in time, it is extremely useful and natural to approach the problem either by trigonometric approximations (analogous to the Fourier series of continuum mathematics) or by statistical analysis (like ensamble averages). Also the classical Fourier transform is suitable to analyze such data, but only to obtain power spectra for vibration and fatigue analysis. It does neither require multi-component measurements nor syncronization to the rotor revolution.

When a detailed description of the vortex structure is desired, the simplest way is to compute the ensamble average and the standard deviation of the signal during successive revolutions of the rotor, as outlined in (1). It must be noted that this technique may describe the overall shape of the wake but not the details of the vortices. This is due to the fact that, at each revolution, the vortex shape is not exactly the same and not exactly at the same place. Because of the very steep gradients in the vortex sheet, anyone of these effects will produce a "smoothing" in any ensamble average in the revolution.

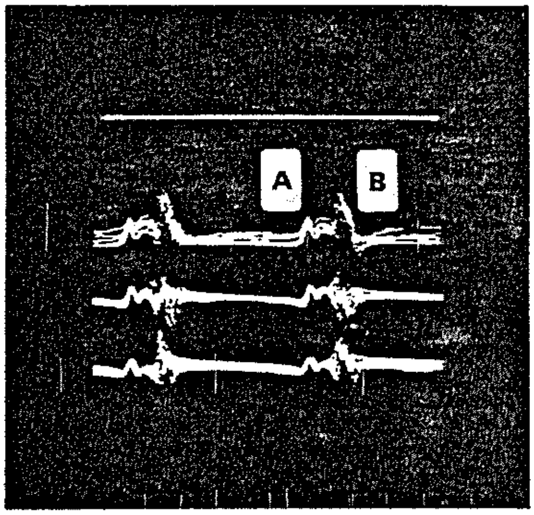


FIGURE 8 The three hot wire signals as a function of azimuth, in 8 successive revolutions. Peak A is due to airfoil thickness and circulation. Peak B is produced by the crossing of a wake.

Two are the possible solutions. The first one is to try an ensamble average syncronized on the peaks themselves, while the second one consists in trigonometric approximation, taking into account also of frequencies much lower than the rotor's fundamental.

The first of theese techniques, not used in the present work, seems to be suitable only for rather "clean" signals, where each single peak can be quite easily identified. The second one is shortly presented in the following.

When trigonometric approximation is used, the series truncation supplies by itself a simple and effective least square approximation. The correcting function, truncated to degree m is of the type:

$$T(x) = 0.5\,A_o + \sum_{k=1}^{m} \left(A_k \cos \frac{2\Pi}{L} kx + B_k \sin \frac{2\Pi}{L} kx \right)$$

where:

$$A_k = \frac{2}{L} \sum_{x=0}^{L-1} y(x) \cos \frac{2\Pi}{L} kx \qquad \text{with } K \text{ from } 0 \text{ to } m$$

$$B_k = \frac{2}{L} \sum_{x=0}^{L-1} y(x) \sin \frac{2\Pi}{L} kx \qquad \text{with } k \text{ from } 1 \text{ to } m$$

and L is the number of (odd!) measured data $y(x)$ at the corresponding x positions.

The degree m of the function $T(x)$ represents a filter and its value can be choosen in such a way to not only correct the input data, but also to help in the description of particular features of the phenomenon under consideration, as shortly outlined in the following.

First of all, the upper limit of the value of m is determined by the cut-off frequency of the instrumentation noise. A second limit is related to the maximum frequency of the turbulence microscale or to the hot-wire resolution (cutoff frequency or measuring volume). Below this second frequency limit, a signal filtering is performed which allows to isolate some peculiar features of the flow. For example, keeping only the lowest frequencies, it is possible to get only the long

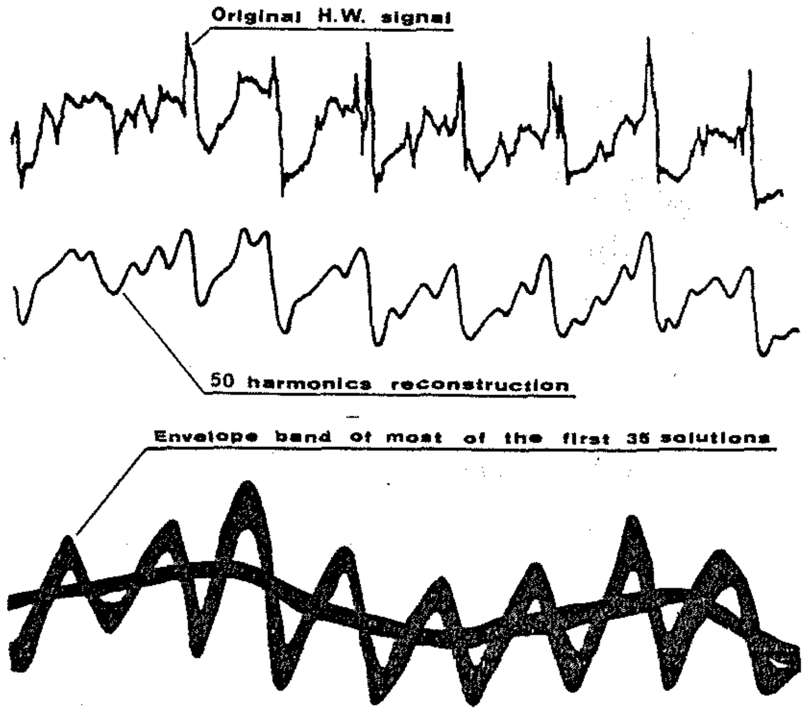


FIGURE 9 Example of a signal reconstruction

The original hot-wire signal, the reconstructed one, and the envelope band of most of the first 35 solutions

period fluctuations. Subtracting them from the signal we may obtain some kind of "unperturbed periodic flow". Another application is to cut off the highest frequencies corresponding to turbulence and vortex cores. Again, by subtraction of a smothed signal we can obtain only turbulence and vortex signal. Furthermore, we can extract a long period and a "blade frequency" signal, and by their crossing detect a reference set of point which is in some way in phase with the vortex peaks. In this way we may later on make the desired ensemble average of the peaks without going through a much more complicated identification procedure.

One interesting feature of this analysis, sa applied to the rotor flow, is that it is possible to separate frequency bands well distinguished. If one takes the whole ensemble of the approximations, starting from m=1, he could notice that many of the approximations tend to collapse on the same curve, one for long period fluctuations, one for blade frequancy and so on. The conclusion is that, being the typical frequencies contained in well separated bands, it is possible , accurate and not critical at all to separate them and to operate on signal bands only.

Figure 9 shows one typical example of this kind of results. On top, we have the original signal, as it is discretized by the computer, containing very steep gradients, turbulence and long period fluctuations. At centre, a reconstruction of the signal keeping the first 50 harmonics. It preserves many of the signal structures, but does not show turbulent fluctuations and the peaks are smoothed. At bottom, an outline of the first 35 approximations, obtained dropping out the isolated curves and saving those that collaps in the most significant bands: note that more than two thirds of the curves are retained.

CONCLUSIONS

Although difficult, the hot-wire analysis of the rotor wake in its three velocity component is possible and givs reliable data. A good choice or a careful manufacturing of the probes, in connection with a good data interpretation and a suitabla data acquisition system are the means of obtaining such results.

The experience obtained in our tests, which had the scope of defining the measuring limits rather than collecting a lot of data, has confirmed that, in our low Reynolds Number model, 256 points per revolution are enough to describe all phenomena including turbulence. Therefore, because we think that some tens of revolutions are enough to describe long period oscillations, a storage between 32 and 64 K is reasonable. It means few seconds for each test and it is an acceptable time.

The kind of data analysis we attempted is suitable for not only a description of the flowfield, but also to isolate various aspects of the signal. Of curse a peak identification would be better for the rather difficult description of the tip vortices, but in that region the flow is not so "clean" to allow simple identification procedures and much more work should be done in this field. Anyhow, our kind of analysis is also suitable for a description of regions of steep change of the signal.

The hot-wire technique, compared to others, mainly to laser anemometry, seems to be good enough, both for limited cost and for bias and seeding problems, which are not yet solved in a reliable way.

The only region of the flowfield for which the fixed hot-wire anemometer is not suitable is, as seen before, the one sweeped by the blades, which contains the very interesting part of the tip vortices. In this region either laser anemometer or flying hot-wire techniques must be applied. Flying hot-wire may be rather difficult for operation with small models, becaause of the high angular speeds, while its application seems to be more feasible on full-scale tests, helping to solve many problems of probe orientation and signal validation. In this case, a large known velocity is added to the one we want to measure; when the former is larger than any value of the latter,there is no sign ambiguity. In any case, the total velocity vector is confined in a much smaller cone.

The final impression is that, at this point, the hot-wire instrumentation is ready for systematical tests in the rotor wake and not only for laboratory studies.

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