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Phase sampling in the analysis of a propeller wake

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Abstract. A phase sampling procedure is used for the analysis of the non-steady, periodic flow field in the near wake of a marine propeller. This method allows to obtain a true ensemble averaging of the experimental measurements. The average is made over a large number of repeated experiments each of which is taken during a complete revolution of the propeller. The measurements are carried out in a recirculating water tunnel with a two-channel laser Doppler velocimeter. The computer-aided evaluation of the experimental results visualizes the following characteristic features of the wake: (1) the vortex sheet developing from the trailing edge; (2) a sudden increase of the axial velocity in the core of the tip vortex; (3) a boundary layer effect near the shaft of the propeller. From the analysis of the direction of vortex rotation along the radial direction of the blade, it is possible to derive information on the working conditions of the propeller.

1 Introduction

Knowledge of the flow field in the near wake, where velocity gradients and turbulence intensities are highest, is important for the design of marine propellers. Theoretical or numerical approaches can not accurately predict the flow field downstream of the propeller. Even the potential theory is not appropriate for giving a reliable picture of such a complex and three-dimensional field.

Therefore, an experimental approach is of particular relevance for this problem. Flow visualization can be used for a qualitative analysis. Hot wire measurements are difficult to perform in the propeller wake, particularly in the near wake, where the presence of the probe would significantly disturb the flow field. Laser Doppler velocimetry (LDV) appears to be the only appropriate technique for analyzing the propeller wake (Kobayashi 1982).

In a tunnel-fixed reference frame (x, y, ϕ'), the phenomenon is non-stationary and periodic (Witze 1977): it is therefore possible to obtain a velocity map in a plane perpendicular to the axis of rotation and in the propeller blade reference system (x, y, ϕ), by moving the measurement point only in radial direction, and by taking the measurement in each point of this radius for one full period of the propeller rotation.

Conventional time averaging of the measured instantaneous velocity cannot be applied to the analysis of the turbulent flow behind the propeller, where the change in the mean flow is periodic ($T = 2\pi/\omega$, ω is the angular velocity). Thus, it is necessary to use phase sampling procedures in order to obtain an ensemble average. For such an averaging process it is necessary to take the experiments over a large number of revolutions of the propeller.

2 Experimental facilities

Measurements are carried out in the Italian Navy recirculating water tunnel. The test section is 0.6 m × 0.6 m in cross-section; the four test section walls are made of perspex, in order to assure a good transparency to laser beams. The maximum water speed is 12 m/s and the turbulence level at the center of the test section is less than 0.5%. A four blade skewed marine propeller is used for the tests (Fig. 1).

A two-channel LDV, working in the reference beam mode, is used to measure the axial and radial components of the velocity, and a rotating diffraction grating is used for obtaining a frequency shift. The signal from a photocell, which determines at each instant the angular position of the measurement point in the blade reference frame,

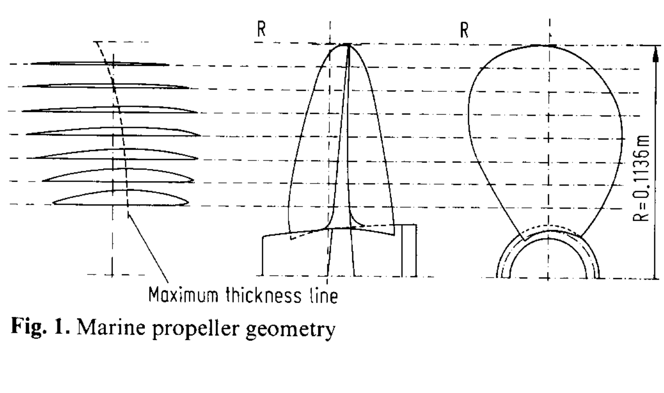


Fig. 1. Marine propeller geometry

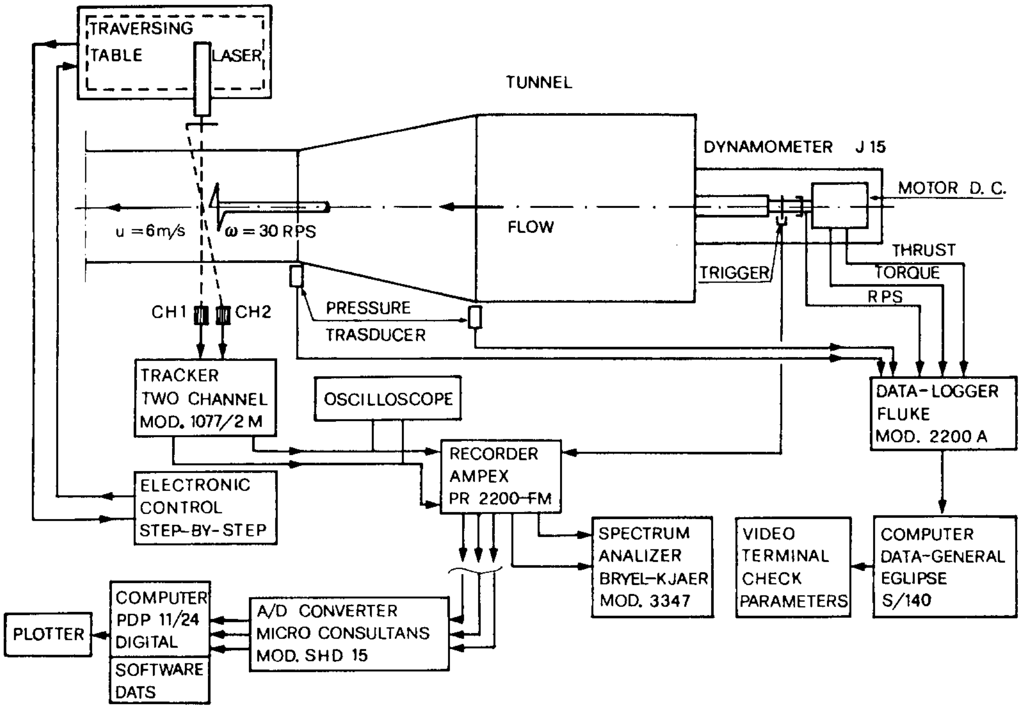


Fig. 2. Experimental set-up and schematic diagram of the signal processing

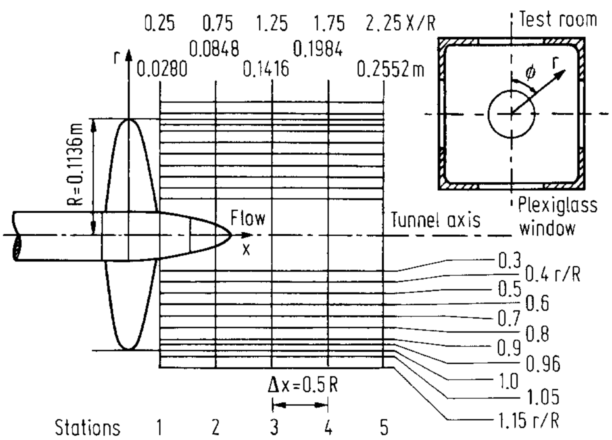


Fig. 3. Marine propeller schematic and measurement points grid

and the two outputs from the blade are digitized and analyzed by a PDP 11/24.

Data acquisition, statistical analysis and plotting of results are performed by DATS software from Prosig Ltd. A schematic representation of the test and measuring set-up is shown in Fig. 2. The grid of measurement points is shown in Fig. 3. Measurements are taken at five axial stations downstream of the propeller and at eleven measurement points in radial direction at each station. The spacing of the radial measurement positions is narrow near the blade tip. All tests are performed with a free upstream water velocity of 6 m/s and a propeller angular velocity of 1,800 rpm.

3 Phase sampling

The mean velocity components $\bar{U}$ and the fluctuating component u can be considered as functions of the angular position $\phi = \phi' + 2\pi\omega$:

$$U(\phi, t) = \bar{U}(\phi) + u(\phi, t)\,. \tag{1}$$

For N revolutions, $\bar{U}$ is evaluated as:

$$\bar{U}(\phi) = \frac{1}{N}\sum_{i=0}^{N-1} U(\phi + i\,2\pi)\,. \tag{2}$$

The turbulence intensity u' therefore is defined by the expression:

$$u'(\phi) = \sigma/\bar{U}\,, \tag{3}$$

where the standard deviation σ is:

$$\sigma = [\overline{U^2(\phi)} - \bar{U}^2(\phi)]^{1/2}\,. \tag{4}$$

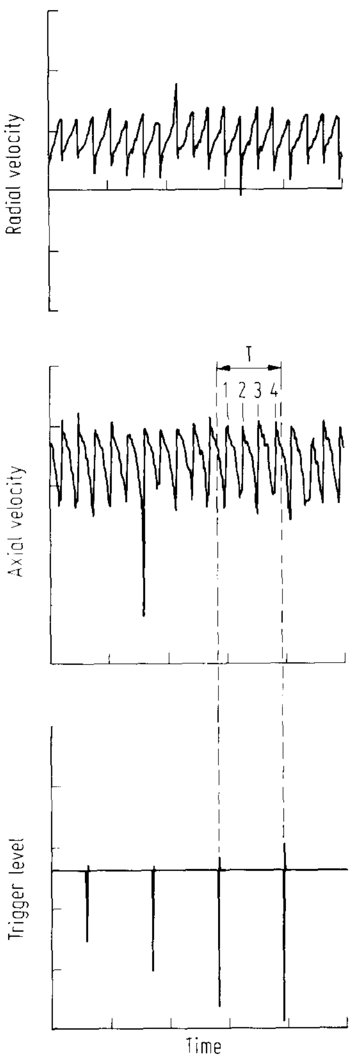
The mean square value can be obtained from the following more general relationship:

$$\overline{U^J}(\phi) = \frac{1}{N}\sum_{i=0}^{N-1} U^J(\phi + i\,2\pi)\,. \tag{5}$$

In a similar way it is possible to determine the skewness S and the kurtosis K by

$$S(\phi) = (\overline{U^3} - 3\bar{U}\,\overline{U^2} + 2\,\overline{U^3})\,\sigma^3\,, \tag{6}$$

$$K(\phi) = (\overline{U^4} - 4\bar{U}\,\overline{U^3} + 6\,\overline{U^2 U^2} - 3\,\overline{U^3})/\sigma^4\,. \tag{7}$$



4 Results

Figure 4 shows the time history of the axial and radial velocity components together with the triggering signal. The drop-out in the axial diagram can be eliminated by means of the software. The first four moments (mean value, variance, skewness, kurtosis) for the axial component of the velocity, at the first station ($x = 0.25R$, $r = 0.80R$) are shown in Fig. 5 as a function of the angular position. The phase sampling is performed for a number $N = 400$ periods at 160 equidistant angular positions within each period. The period of the flow field is one-fourth of the period of revolution because the four propeller blades are identical.

In the velocity diagram it is possible to observe the velocity defect at the angular position ϕ_{TE} where the two boundary layers from both sides of the blade merge downstream of the trailing edge. The presence of this wake is better shown in form of the peak maxima of the standard deviation plot. The loss of the periodic character in the higher order averagings is evident in the diagrams of skewness and, particularly, kurtosis. This is due to the increase of the confidence interval associated to the increase of the moments' order. A systematic negative skewness appears at the trailing edge.

A high maximum of the axial velocity can be observed at the first station, near the tip blade. This maximum is

Fig. 4. Axial and radial velocity components and signal from the photocell indicating the beginning of each new period. Each period of length T includes 4 peaks, each related to one of the 4 propeller blade

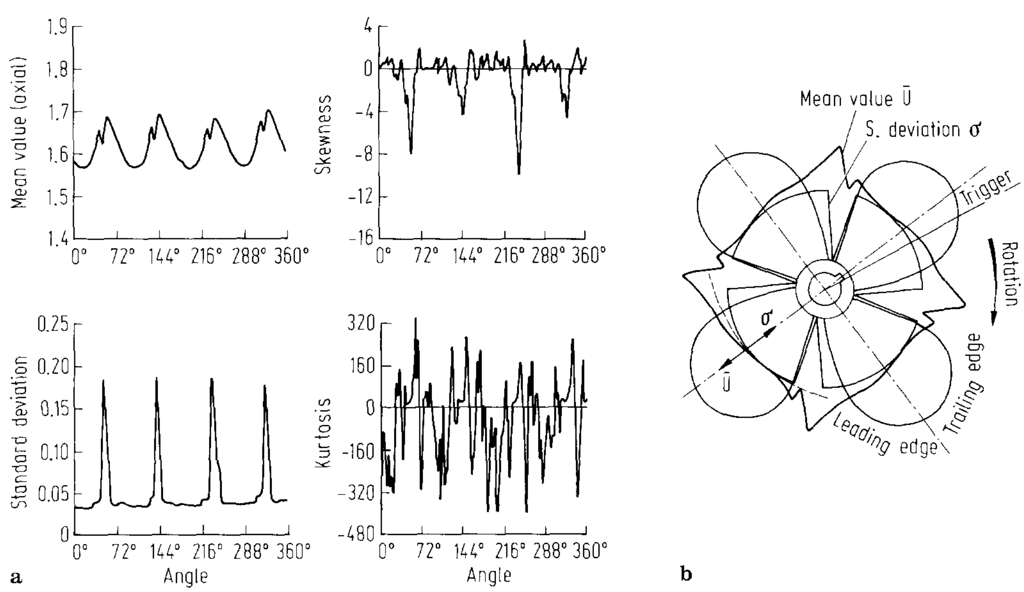


Fig. 5. a Mean value of axial velocity, standard deviation of axial velocity, skewness and kurtosis for the axial velocity component at $x = 0.25R$, $r = 0.70R$; **b** mean value and standard deviation in polar diagrams

connected with the tip vortex which induces an increase of velocity (Batchelor 1960; Accardo et al. 1984). If one neglects any losses, this velocity is given by:

$$U_x^2 - U_\infty^2 = \int_0^\infty \frac{1}{2\pi\zeta}\frac{\partial \Gamma^2}{\partial \zeta}\, d\zeta \,. \qquad (10)$$

These two effects are demonstrated more clearly in a three-dimensional representation of the axial velocity and the turbulence intensity at different stations (Figs. 6 and 7). In downstream direction, the value of the velocity maximum in the core of the tip vortex decreases, and the transverse dimension of the vortex increases.

The form of the wake is brought out by the pattern of the turbulence intensity (Fig. 7). For each axial position the wake is located at the respective maximum of the standard deviation. In this way it is possible to see the wake shape and the roll-up near the tip vortex, where a maximum peak appears. As one proceeds downstream, the turbulence diffusion smooths down the standard deviation peaks. The high turbulence values near the axis of rotation are due to the presence of the boundary layer which develops around the propeller shaft.

Figure 8 shows the angular distribution of the turbulence intensity for two radial positions, i.e., on the surfaces of two cylinders being coaxial to the axis of rotation. For $r/R = 0.9$, a contraction of the stream tube becomes evident. In fact, only at the first two axial stations one notices the characteristic peaks caused by the vortex sheets. Downstream of these stations one observes an almost constant turbulence level not very different from the level observed in the external flow. The diagram for $r/R = 0.3$ shows the skew of the wake in downstream direction.

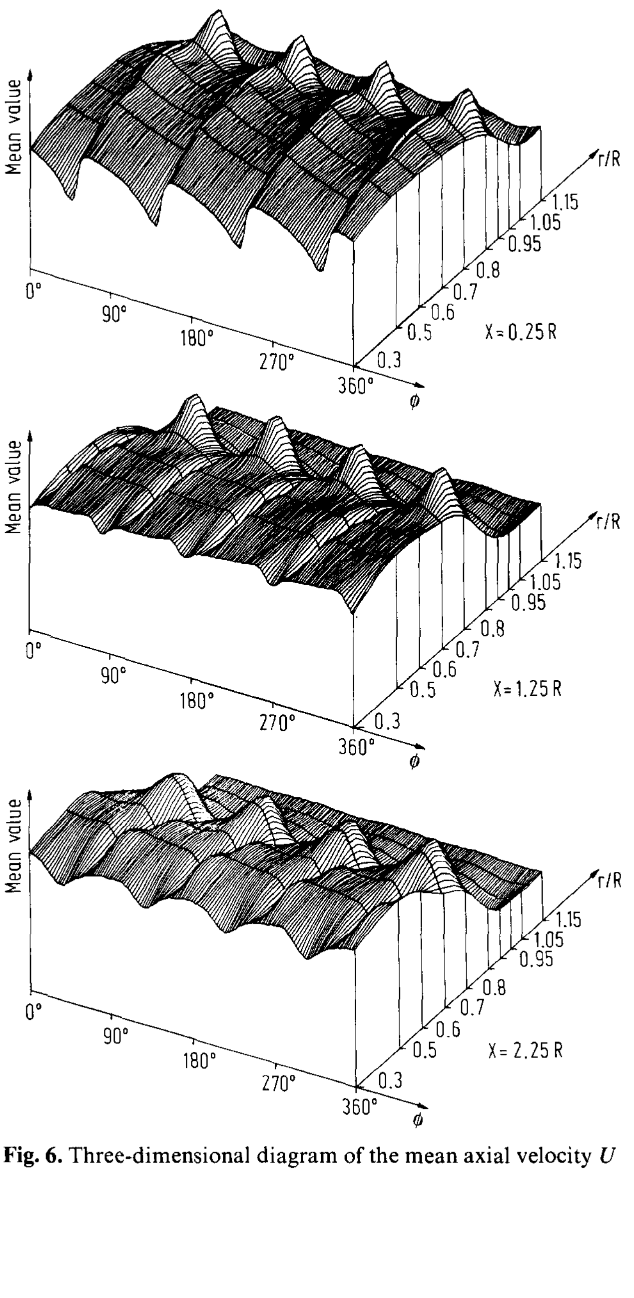


Fig. 6. Three-dimensional diagram of the mean axial velocity U

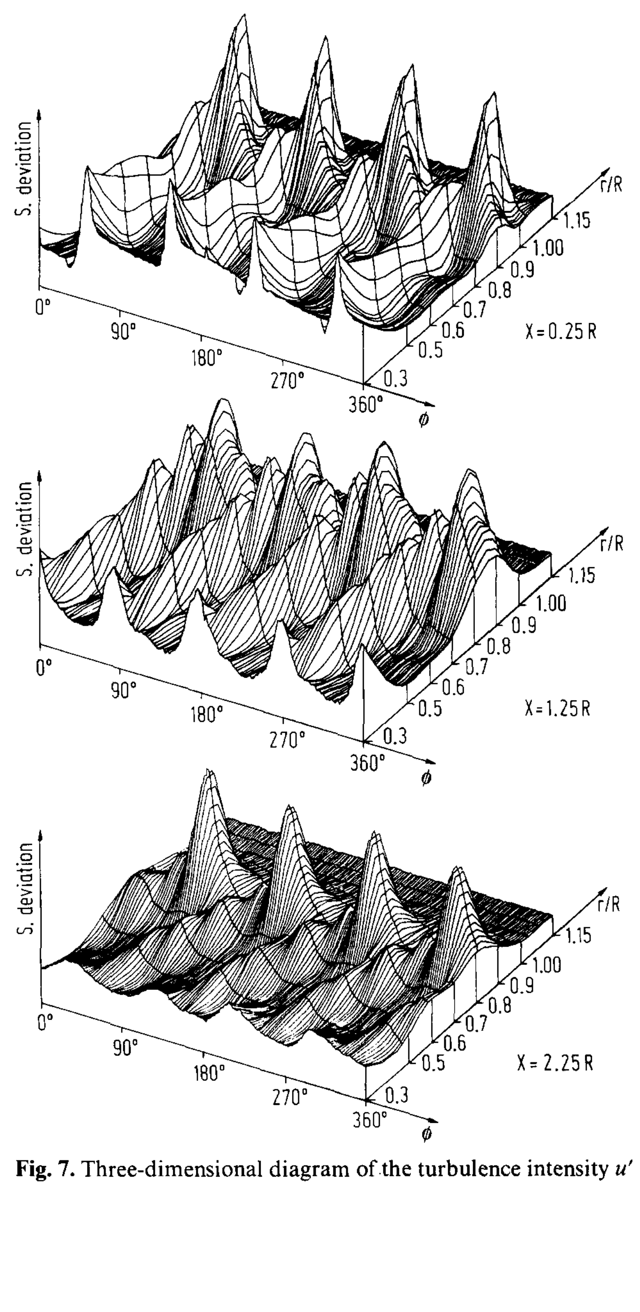


Fig. 7. Three-dimensional diagram of the turbulence intensity u'

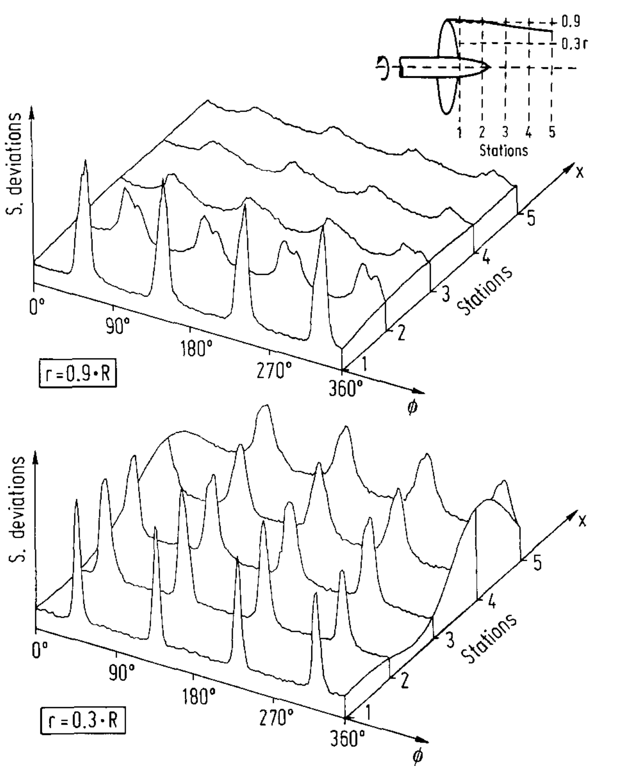


Fig. 8. Standard deviation for the axial velocity component at two given radial positions

The behaviour of the radial velocity component permits to identify the position of the vortex core and its direction of rotation. The radial velocity component v is positive when it is directed towards the axis.

The three diagrams of the radial velocity (Fig. 9) refer to three radial positions between the root and the tip of the blade. The straight parts of the curves represent the cores of the vortices. The vortex center is located at the angular position of the peak of the turbulence intensity. The direction of rotation is reversed when one moves from the root to the tip: this behaviour makes evident that, at this particular velocity, the propeller is not operating at design conditions.

The same behaviour is seen in Fig. 10, where the radial velocity component in the same section is given. This figure is particularly useful for demonstrating that, in a particular range, the radial velocity component is oriented towards the tip (negative v), while the rest of the flow is generally oriented towards the axis. This behaviour is due to the entrainment of fluid close to the tip vortex.

5 Conclusions

The flow field in the near wake of a marine propeller is analyzed quantitatively by means of the laser Doppler

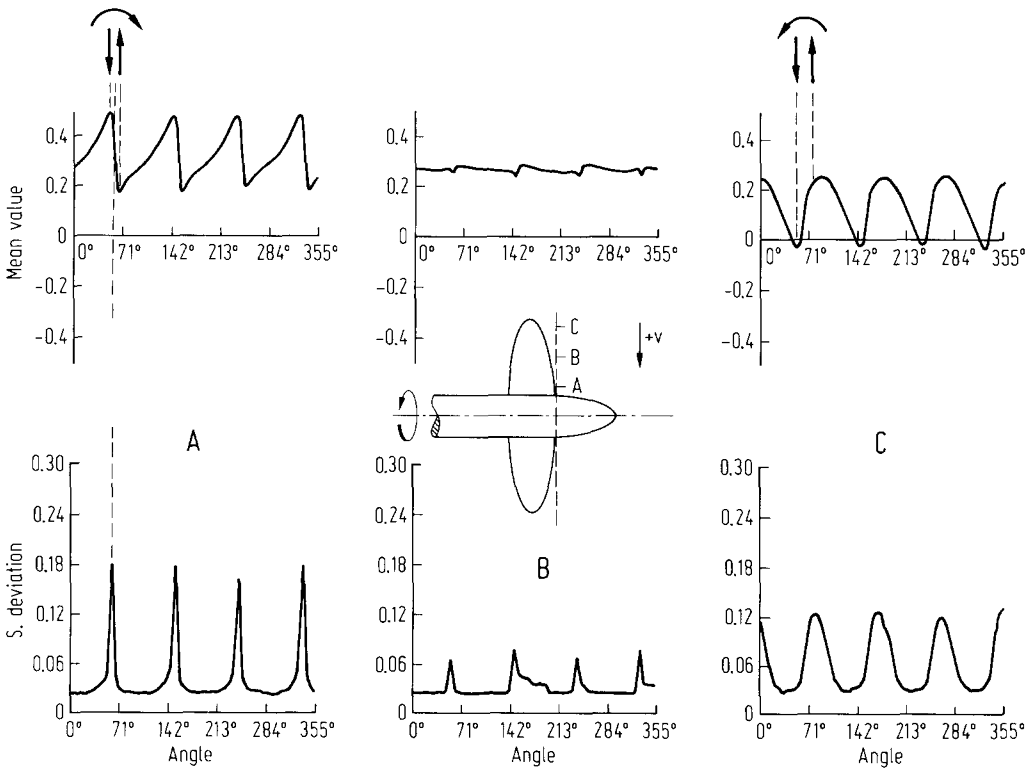


Fig. 9. Mean value and standard deviation of radial velocity component at the first axial station for three different radial positions

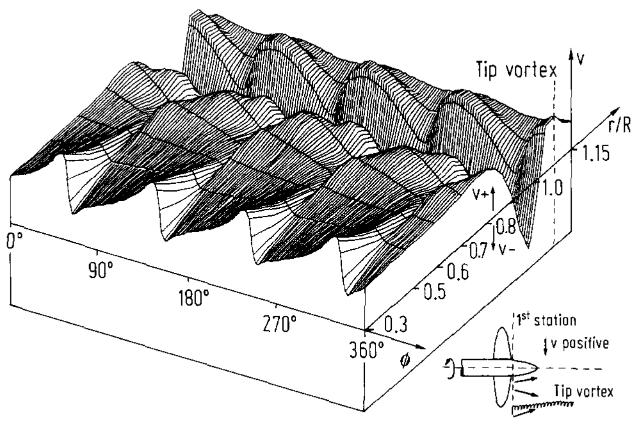


Fig. 10. Radial velocity component at the first station

velocimeter which provides a high spatial resolution and a suitable resolution in time without perturbing the field.

A large amount of data is necessary for giving a detailed description of the flow and for performing an accurate ensemble averaging. The large amount of data can be handled by a computer, which also allows for the further analysis of the data measured in the complex, three-dimensional flow.

From the analysis of the axial and radial velocity components and particularly the turbulence intensity, the following characteristics of the reported fluid-dynamic field are observed:

- the vortex sheet from the blade trailing edge;
- the peak maxima of the axial velocity in the core of the tip vortex;
- the stream tube contraction in downstream direction;
- the out-of-design condition when the direction of the vortex rotation near the axis is different from that near the tip of the blade;
- the presence of the shaft boundary layers.

It is believed that the most important result is the verification that the propeller, at this particular velocity of rotation, is operating out-of-design, and that a physical explanation for this finding can be given. Preliminary measurements show that the situation can be improved by increasing the velocity of rotation. These measurements indicate that at approximately 2,250 rpm there is no change in the direction of vortex rotation, i.e. the propeller is then operating at design conditions. The method described in this paper will be used for more detailed investigations of the propeller characteristics.

References

Accardo, L.; Cenedese, A.; Cioffi, F. 1984: Experimental analysis of tip vortex by laser Doppler anemometry. Proceed. Int. Conf. on Laser Anemometry – Advances and Applications, pp. 257–277. BHRA, The Fluid Engineering Centre, Cranfield, Bedford MK G3 OA5, U.K.

Batchelor, G. K. 1960: Axial flow in trailing linear vortices. J. Fluid Mech. 20, 645–658

Kobayashi, S. 1982: Propeller wake survey by laser-doppler velocimeter. Proceed. Int. Symp. on Application of Laser-Doppler Anemometry to Fluid Mechanics, Lisbon, Paper no. 18.4

Witze, P. O. 1977: Hot-wire measurement of the turbulence structure in a motored spark-ignition engine. Report No. SAND80-0132, Sandia Laboratories, Albuquerque/USA

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