The objective of this work was to enhance the understanding of unsteady flow phenomena in multistage low-pressure turbines. For this purpose, hot-film probe measurements were made downstream of every rotor blade row of a five-stage low-pressure turbine. Rotor-rotor interaction and stator-rotor interaction were observed to have a profound influence on the flow through the low-pressure turbine. Interaction of rotors of different turbine stages occurred owing to the influence of the wakes shed by one rotor blade row upon the flow through the next downstream rotor blade row. This wake-induced rotor-rotor interaction resulted in strongly amplitude-modulated periodic and turbulent velocity fluctuations downstream of every rotor blade row with the exception of the most upstream one. Significantly different wake depths and turbulence levels measured downstream of every rotor blade row at different circumferential positions evidenced the effect of the circumferentially non-uniform stator exit flow upon the next downstream rotor blade row. Stator-rotor interaction also strongly influenced the overturning and the underturning of the rotor wakes, caused by the rotor secondary flows, in the rotor endwall regions. Low rotor wake overturning and underturning, i.e., reduced rotor secondary flow influence, were observed to correlate well with low rotor wake turbulence levels.

INTRODUCTION

The unsteady flow in a turbomachine resulting from the relative motion of neighboring blade rows causes various interactions between the blade rows that may influence both the aerodynamic and the structural behavior as well as the noise emission of the rotor blades and the stator vanes of the turbomachine. The potential flow interaction between two blade rows moving relative to each other arises because of the circulation about the blades and because of the potential fields, other than circulation, about the blades that are due to the finite thickness of the blades (Lefcort, 1965). The potential flow fields about a blade extend both upstream and downstream of the blade, and decay exponentially with a length scale of the order of the chord. The wake interaction refers to the unsteadiness induced at a blade row by the wakes shed by the blades of an upstream blade row and hence convected downstream (e.g., Binder et al., 1985). Owing to the slow decay of wakes, the wake interaction persists significantly farther downstream than the potential flow interaction. In the endwall regions, the unsteadiness caused by secondary flows and associated vortices does also contribute to the blade row interactions (e.g., Binder et al., 1987, and Sharma et al., 1988).

In transonic turbomachines, further interactions arise from the impingement of the trailing edge shock wave of one blade row upon the immediate downstream blade row (e.g., Guenette et al., 1989, and Doody and Oldfield, 1985). The turbine investigated herein, the low-pressure turbine of an aircraft engine, is a multistage, subsonic, moderately high-aspect-ratio turbine. Therefore, with the exceptions of the endwall regions, interactions between different blade rows are due to wake interaction and possibly also potential flow interaction. Wake induced transition has been observed to have a profound effect upon the boundary layer behavior of blade rows operating under conditions typical to those found in low-pressure turbines (e.g., Schröder, 1989, and Hodgson and Addison, 1989). It is thus of great importance to correctly assess the perturbations a blade row is subjected to owing to oncoming wakes. In this investigation unsteady velocity measurements were made using hot-film probes at two circumferential positions, referred to as Position A and Position B, downstream of every rotor blade row of the low-pressure turbine. The measurements were carried out at design pressure ratio and corrected speeds at Re numbers of 120000 (corresponding to high altitude cruise), 170000 (corresponding to cruise) and 220000, with the rig Re number based on the chord length and on the exit flow conditions of the first stage stator vane. The distance in the circumferential direction between any of the two measurement positions downstream of a rotor blade row equalled a multiple plus one half of the spacing of the immediate upstream stator vanes. Hence, the analysis of the measurements permits the assessment of the influence of the nonuniform stator exit flow on the flow through the immediate downstream rotor blade row and also permits the assessment of the effects on the flow through the turbine that are due to interaction of different rotor blade rows. By regarding turbulence levels and wake depths downstream of the individual rotor blade rows the hot-film probe measurements also help evaluate the performance of the individual rotor blade rows and help detect operating conditions for which flow separation occurs.

TEST FACILITY AND INSTRUMENTATION

The experiment was carried out in the five-stage low-pressure turbine shown in Figure 1, installed in the high altitude test facility at Stuttgart University. Unsteady velocity measurements were made by radially traversing hot-film probes at two circumferential positions downstream of all five turbine rotors, Figures 1 and 2. Down-
stream of Rotors 1 to 4 the distances in relative flow direction between the respective hot-film probes and the respective rotor blade trailing edges were slightly less than one chord, Table 1. Owing to mechanical design constraints the measurements downstream of Rotor 5 had to be made at a significantly larger distance away from the rotor blade trailing edge. Thus, the fluctuations measured downstream of Rotor 5 could not be compared to those measured downstream of the other four rotors and will therefore not be discussed in this paper.

<table>
<thead>
<tr>
<th>Measuring Plane</th>
<th>Distance between Hot-Film Probe and Rotor Blade Trailing Edge (in relative flow direction at midspan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85 chord</td>
</tr>
<tr>
<td>2</td>
<td>0.88 chord</td>
</tr>
<tr>
<td>3</td>
<td>0.73 chord</td>
</tr>
<tr>
<td>4</td>
<td>0.63 chord</td>
</tr>
<tr>
<td>5</td>
<td>4.37 chord</td>
</tr>
</tbody>
</table>

Table 1 Location of measurement positions

DANTEC 55 R03 hot-film probes were used for this investigation. The probes were arranged so that they were sensitive to the axial and circumferential velocity components of the flow, Figure 2. Hence, the magnitude of the component of the velocity vector in the plane spanned by vectors in the circumferential and in the axial direction was measured in this investigation. The probes were connected to a TSI Model 1050 anemometer operating in constant-temperature mode. The probe signals were linearized prior to recording. (For a detailed description of the data recording and the data reduction procedure see Schröder, 1989.)

The setting parameters of the linearizer, i.e., the coefficients for the polynomial used for linearizing, were determined in a calibration procedure at constant density. Since the density in a turbine decreases in flow direction from one rotor to the next, using identical coefficients for linearizing signals of hot-film probes in a multistage turbine may result in measurement errors. In this investigation only fluctuating signals normalized by the time mean signal are presented. Data from a hot-wire calibration made at different densities were used to estimate the magnitude of the measurement error on the thus normalized fluctuating signals. It was found that the amplitudes of the fluctuations were underestimated for low densities when the linearization was carried out with the linearization coefficients determined at significantly higher densities. Under the assumption that the density dependence of the calibration is similar for hot-wires and for hot-films, the amplitudes of the fluctuations presented in this investigation are thus underestimated by up to 20%, with the largest error occurring for the lowest density observed in the experiment, i.e., downstream of the last turbine stage for the lowest rig Re number. Although a measurement error of this size would not be acceptable if a quantitative analysis of the flow through the turbine was attempted, the quality of the measurements was considered sufficient for the purpose of this investigation, namely, to enhance the understanding of unsteady flow phenomena in multistage turbines, in particular of the effects of rotor-rotor interaction and of stator-rotor interaction on the flow through the turbine.
DATA REDUCTION

Owing to the superposition of periodic and random fluctuations, a direct analysis of the linearized hot-film probe signals would have been extremely difficult to perform. To separate the periodic and the random fluctuations in the signals, the unsteady data were ensemble averaged. The ensemble-averaged periodic fluctuations and the ensemble-averaged root-mean-square of the random fluctuations, in the following referred to as the ensemble-averaged turbulent fluctuations, were obtained by:

\[ \bar{c}_j(t) = \frac{1}{N} \sum_{k=1}^{N} c_{k,j}(t) \]
\[ \bar{c}_j^2(t) = \frac{1}{N-1} \sum_{k=1}^{N} (c_{k,j}(t) - \bar{c}_j(t))^2 \]

where \( N \) is the number of averaging periods, \( k \) denotes the \( k \)'th averaging period, and \( j \) denotes the \( j \)'th data point in any of the \( N \) averaging periods. As averaging period two rotor revolutions were chosen. About 1600 data points were taken per rotor revolution. A total of 500 averaging periods were found to be sufficient for the ensemble-averaging process. The time-averaged velocity and the time average of the ensemble-averaged turbulent fluctuations were obtained by integration of the ensemble-averaged periodic and the ensemble-averaged turbulent fluctuations,

\[ \bar{c} = \frac{1}{T_R} \int_0^{T_R} \bar{c}(t) \, dt \]
\[ \bar{c}' = \frac{1}{T_R} \int_0^{T_R} \bar{c}'(t) \, dt \]

The ensemble-averaged periodic, and the time-averaged and the ensemble-averaged turbulent fluctuations at the different radial positions downstream of the rotors are presented normalized by the time-averaged velocities at the respective radial position.

DISCUSSION OF RESULTS

Time-Averaged Turbulent Fluctuations

To provide an initial overview of the flow through the turbine the time-averaged turbulent fluctuations at the two measurement positions downstream of every rotor are presented in Figure 3 for the three Re numbers investigated. Some important information about the flow can be gleaned from these data.

The largest turbulent fluctuations occur in the endwall regions. These large turbulent fluctuations that are ascribed to the rotor secondary flows extend from the tip significantly farther into the blade channel than from the hub. This is due to the radial pressure gradient that tends to elongate the tip passage vortex towards midspan and tends to squeeze the hub passage vortex onto the hub. Downstream of Rotor 1, especially at Position A in the midspan and in the tip region, a significant decrease of the turbulent fluctuations occurs with increasing Re number, in particular with the increase from 120000 to 170000. This strong drop of the turbulent fluctuations with increasing Re number downstream of Rotor 1 suggests laminar separation on either the first stage stator or the first stage rotor at a Re number of 120000. Downstream of Rotor 2 to 4 no significant Re number dependence of the turbulent fluctuations occurs. The slight increase of the turbulent fluctuations with increasing Re number, observed in particular in the endwall regions, is of the same order of magnitude as the measurement error incurred by the constant-density calibration of the hot-film probes. Therefore the turbulent fluctuations downstream of Rotors 2 to 4 are considered Re number independent.

Comparing these results to those of an earlier investigation reported by Binder et al. (1989) in which results of hot-film probe measurements made at one circumferential position downstream of Rotors 2, 4, and 5 were reported, good agreement was found for the time-
averaged turbulent fluctuations downstream of Rotor 2 over the entire Re number range and for the time-averaged turbulent fluctuations downstream of Rotor 4 for the lowest Re number investigated, Re = 120000. In the earlier investigation, however, a strong decrease of the turbulent (and also of the periodic) fluctuations was observed downstream of Rotor 4 when the Re number was increased from 120000 to 170000. To find an explanation for this significantly different Re number behavior downstream of Rotor 4, the steady wall pressure measurements downstream and upstream of Rotor 4 as well as the steady surface pressure measurements on Stators 4 and 5 were scrutinized, but no significant Re number dependency was found for any of these measurements. It was thus concluded that the strong decrease of the turbulent fluctuations with increasing Re number observed in the earlier investigation was most likely due to a measurement error.

Ensemble-Averaged Periodic and Turbulent Fluctuations

The ensemble-averaged periodic and turbulent fluctuations at mid-span downstream of Rotors 1 to 4 are shown in Figures 4 and 5 for the two circumferential positions and a rig Re number of 170000. The length of the abscissa corresponds to slightly more than one rotor revolution. In the traces of the periodic fluctuations the downward pointing peaks identify the rotor wakes characterized by a velocity deficit compared to the velocity in the rotor core flows that are identified by the upward pointing peaks. The periodic fluctuations do occur between the two circumferential positions downstream of every rotor. These differences are most striking downstream of the first stage rotor where the velocity deficit in the wake is about 10% of the mean velocity at Position A and about 22% of the mean velocity at Position B. Correspondingly, the turbulent fluctuations are significantly larger at Position B than at Position A. These differences clearly show the influence of the first stage stator exit flow onto the flow through the first stage rotor.

Significantly amplitude-modulated periodic and turbulent fluctuations are a salient feature of the flow downstream of Rotor 2 and, albeit to a lesser extent, also downstream of Rotors 3 and 4. The amplitude modulation of the periodic and the turbulent fluctuations comes about because of the influence the wakes that are shed by the rotor blade row immediately upstream of the one investigated exert on the flow through the next downstream rotor blade row (Binder et al., 1989). The mechanism of this wake-induced, downstream rotor-rotor interaction will be described in detail later in this paper. That the amplitude-modulated fluctuations are indeed the result of a downstream rotor-rotor interaction can easily be inferred by comparing the number of nodes and antinodes occurring over one rotor revolution to the difference in the blade count between a particular rotor blade row and the rotor blade row immediately upstream of it. The differences in the blade count for Rotor 1/Rotor 2, Rotor 2/Rotor 3, and Rotor 3/Rotor 4 are 2, 12, and 2, respectively. Correspondingly, downstream of Rotors 2, 3, and 4 the number of nodes and antinodes occurring over one rotor revolution are 2, 12, and 2, respectively, as can be seen from Figure 4. The 2 trough-2 peak undulation over one rotor revolution of the turbulent fluctuations downstream of Rotor 3 at Position A reveals the influence of the Rotor 1-Rotor 2 interaction onto the flow through Rotor 3. This influence is, however, only noticed in the turbulent fluctuations and not in the periodic fluctuations.

Significant upstream interaction, i.e., a strong influence of a rotor blade row on the flow through an upstream rotor blade row is not observed. Only downstream of Rotor 2 at Position B, a weak influence of a downstream rotor blade row, Rotor 3, can be detected in the wake measurements. This is to say that superimposed to the dominating 2 node-antinode structure a weak 12 node-antinode structure can be identified in the periodic fluctuations downstream of Rotor 2. Recalling that the difference in the blade count between Rotor 2 and Rotor 3 is 12, this weak 12 node-antinode structure in the periodic fluctuations downstream of Rotor 2 shows the upstream influence of Rotor 3 on the flow through Rotor 2. Compared to the downstream influence of Rotor 1 on the flow through Rotor 2 this upstream influence of Rotor 3 is small. Hence, in this turbine wake-induced interaction is the dominant interaction mechanism between rotor blade rows.

The differences in the velocity deficit in the wakes downstream of Rotor 2 because of this rotor wake interaction, 8% of the mean velocity in the nodes and 20% of the mean velocity in the antinodes, however, are comparable to the differences in the velocity deficit in the wakes downstream of Rotor 1 because of stator-rotor interaction. Both effects, stator-rotor and rotor-rotor interaction, are therefore of comparable significance for the flow through this turbine.

Although significant differences in wake depth were observed as a result of stator-rotor and rotor-rotor interaction, blade row separation owing to stator-rotor or rotor-rotor interaction cannot be inferred from the velocity deficit in the rotor wakes. For in order to apply the velocity deficit in the rotor wakes as a criterion for rotor blade separation, the velocity deficit has to be considered in the relative frame of reference rather than in the absolute frame of reference in which the measurements were made and for which the model lines of flow were determined. Since no flow angle measurements were made, an exact transformation from the absolute frame to the relative frame was not possible. Consequently, simplifying assumptions on the flow angle had to be made to approximately calculate the velocity deficit in the relative frame. The calculation showed that for this particular turbine a wake velocity deficit at midspan of 20% in the absolute frame translates to a velocity deficit of about 10% - 12% in the relative frame normalized by the mean velocities in the absolute and in the relative frame, respectively. However, a velocity deficit of about 10% - 12% measured in the wakes of a blade row at a distance of approximately 0.7 chord downstream of the blade trailing edge in flow direction is by itself not sufficient to permit a rotor blade separation. (Compare, e.g., Figure 9 that presents the velocity contours downstream of Stator 1 measured in a cascade test. The velocity deficit in the stator wakes at midspan is about 10%. Flow visualization showed the occurrence of a laminar separation bubble and subsequent flow reattachment.) Notwithstanding, the temporal nonuniformity of the rotor exit flow that is due to rotor-rotor interaction significantly influences the boundary layer transition on the immediate downstream stator, as results of surface hot-film gage measurements on the stator vanes of this turbine showed, Schröder (1990).

Stator-Rotor Interaction (Measurements downstream of Rotor 1)

Contour plots of the ensemble-averaged periodic and turbulent fluctuations downstream of Rotor 1 are presented in Figures 6 and 7 for a Re number of 220000. (The radial positions at which the measurements were made are indicated by the short lines at the right bound ary of the contour plots.) Turning first to the contour plots of the turbulent fluctuations, Figure 6, it can be seen that in the midspan region the turbulent fluctuations in the rotor wakes as well as in the rotor core flows are higher at Position B than at Position A; see also Figure 8 for the turbulent and the periodic fluctuations downstream of Rotor 1 at 50% span.

The phase difference between the minimum of the periodic fluctuations and the maximum of the turbulent fluctuations that are presented in Figure 8 comes about because the measurements were made and are presented for the absolute frame of reference. Note that while the maximum of the turbulent fluctuations within a rotor blade passing period is independent of the frame of reference, the minimum of the periodic fluctuations depends on the frame of reference. Assuming that in the relative frame of reference the maximum of the turbulent fluctuations occurs when the minimum in the periodic fluctuations is attained, i.e., when the velocity deficit in the rotor wakes is largest, the transformation from the relative frame to the absolute frame - for this particular turbine - will result in a phase shift of the minimum of the periodic fluctuations so that the
maximum of the turbulent fluctuations is found on the pressure side flank of the rotor wake.

The level of the turbulent fluctuations in the core flow downstream of a blade row reflects for the most part the level of the turbulent fluctuations in the flow upstream of the blade row. For this reason the measurements in the midspan region at Position A were inferred to have been made in the Stator 1 core flow, i.e., with the Stator 1 core flow impinging upon the Rotor 1 blades, and the measurements in the midspan region at Position B were inferred to have been made in the Stator 1 wake flow, i.e., with the Stator 1 wake flow impinging upon the Rotor 1 blades. At both circumferential positions, the turbulent fluctuations increase strongly towards the tip with - as in the midspan region - significantly higher turbulent fluctuations occurring at Position B. The turbulent fluctuations also increase towards the hub, but the high fluctuations near the hub do not extend as far into the blade channel as those near the tip. In contrast to the midspan and the tip region, the higher turbulent fluctuations near the hub occur at Position A and not at Position B. This suggests that the Stator 1 wake flow is inclined against the radial direction so that the measurements obtained downstream of Rotor 1 at Position A near the hub were made in the Stator 1 wake flow and those in the midspan and in the tip region were made in the Stator 1 core flow, whereas the measurements obtained at Position B near the hub were made in the Stator 1 core flow and those in the midspan and in the tip region were made in the Stator 1 wake flow.

That the Stator 1 wake is indeed inclined against the radial direction can be seen from the velocity contours measured downstream of Stator 1 in a cascade test, Figure 9. The positions of the radial traverses downstream of Rotor 1 relative to the Stator 1 exit flow as inferred from the analysis of the contour plots of the ensemble-averaged turbulent fluctuations are indicated by a dashed line, Position A, and by a straight line, Position B. (The lines are half a Stator 1 spacing apart, of course.)

The effects of the nonuniform Rotor 1 inflow are also evident in the contour plots of the ensemble-averaged periodic fluctuations, Figure 7. The dashed lines in Figure 7 indicate the times at which fluid particles leaving the rotor blade trailing edge at the same instant of time should arrive at the hot-film probe if both flow angle and flow velocity corresponded to their respective design values.

Turning first to the flow at midspan (see also Figure 8), significantly different wake shapes and wake velocity deficits are observed at Positions A and B. At Position A (with the Stator 1 core flow impinging upon the Rotor 1 blades) the velocity deficit in the rotor wakes was found to be approximately 10% of the mean velo-
Figure 6 Contour plot of the ensemble-averaged turbulent fluctuations downstream of Rotor 1 (Re=220000, Positions A and B)

ity, and the rotor wakes had not coalesced at the measurement position. At Position B (with the Stator 1 wake flow impinging upon the Rotor 1 blades), however, the velocity deficit in the rotor wakes was significantly larger than at Position A, approximately 22% of the mean velocity. Also in contrast to Position A, the rotor wakes had coalesced. This shows clearly that both significant temporal and spatial nonuniformities exist downstream of a turbine stage.

The most salient differences between the two circumferential positions, however, occur in the endwall regions. Regarding first the measurements in the hub region at Position A, it can be seen that in the region from 40% span to 20% span the rotor wakes arrive at earlier times at the hot-film probe as the measurements are made closer to the hub, whereas in the region from 20% span to 5% span the rotor wakes arrive at later times at the hot-film probe as the measurements are made closer to the hub. Therefore, at 20% span, the rotor wakes arrive earlier at the measurement probe than at any other spanwise location. Thus, the wake traces in the radial direction, i.e., the locations of the minimum velocity in the rotor blade passing periods at different radial positions, form into single zigzags with a sharp turn at 20% span. These wake traces indicate flow underturning at 20% span (early arrival of the wake flow at the measurement probe owing to a decrease in the flow angle, measured against the axis of rotation) and underturning close to the hub at 5% span (late arrival of the wake flow at the measurement probe owing to an increase in the flow angle). This pattern of underturning and underturning reveals the presence of a strong hub passage vortex (that tends to overturn the fluid close to the hub and to underturn the fluid at some spanwise position, depending upon the strength of the vortex, away from the hub). At the other circumferential position, Position B, only weak underturning of the rotor wakes, closer to the hub than at Position A, is observed. This suggests a significantly stronger hub channel vortex at Position A than at Position B. The turbulent fluctuations in the hub region are significantly higher at Position A than at Position B so that regions of high turbulent fluctuations correlate well with regions of strong rotor wake distortion, i.e., strong underturning and underturning of the rotor wakes due to the hub passage vortex.

In the tip region, the wake traces in the radial direction form an almost straight line at Position A, but form into zigzags at Position B. This zigzag pattern of the rotor wakes observed at Position B is, as already pointed out, indicative of wake distortion that is due to rotor secondary flow. The wake traces observed at the two circumferential positions therefore reveal strong secondary flow influence at Position B and only weak secondary flow influence at Position A. This notion is enforced by the occurrence of lumps of high turbulent fluctuations in the tip region at Position B that are indicative of the high turbulent fluctuations associated with strong secondary flows. In contrast, no such lumps of high turbulent fluctuations occur in the tip region at Position A. Thus, at the tip, the stronger secondary flow influence occurs at Position B. At the hub, however, the stronger secondary flow influence occurs at Position A. This reflects the influence of the inclined Stator 1 wake (note that the analysis of the contour plots of the turbulent fluctuations measured downstream of Rotor 1 in conjunction with the results of velocity measurements downstream of Stator 1 showed that the measurements downstream of Rotor 1 at Position A were made in the Stator 1 wake flow near the hub and in the Stator 1 core flow near the tip, whereas the measurements at Position B were made in the Stator 1 core flow near the hub and in the Stator 1 wake flow near the tip). Reduced secondary flow influence in turbines caused by stator-
Figure 7 Contour plot of the ensemble-averaged periodic fluctuations downstream of Rotor 1 (Re=220000, Positions A and B)

Figure 8 Ensemble-averaged periodic and turbulent fluctuations at midspan downstream of Rotor 1 (Re=220000, Positions A and B)

Figure 9 Velocity contours downstream of Stator 1 measured in a cascade test (Re=180000)
Rotor interaction has also been reported by Sharma et al. (1988) and Hebert and Tiederman (1989).

Rotor-Rotor Interaction (Measurements downstream of Rotor 2)

In the discussion of the measurements made at midspan downstream of Rotors 1 to 4, it was pointed out that amplitude-modulated periodic and turbulent fluctuations owing to wake-induced, downstream rotor-rotor interaction were a salient feature of the flow downstream of Rotor 2 and, albeit to a lesser extent, also downstream of Rotors 3 and 4. To qualitatively describe the mechanism of wake-induced rotor-rotor interaction, a schematic illustration of the Rotor 2 inflow conditions is presented in Figure 10 (Binder et al., 1989). The wakes shed by the Rotor 1 blades are cut and distorted by the Stator 2 vanes and thereby formed into wake segments that are convected downstream with the Stator 2 flow. The thick, broken lines indicate the Stator 2 wakes, and therefore the flow direction in the absolute frame of reference. Regarded from the relative frame of reference, the Rotor 1 wake segments are arranged in wake avenues marked in Figure 10 by lines and circles. Owing to the different blade counts of Rotors 1 and 2, the Rotor 1 wake segments following these wake avenues will enter subsequent Rotor 2 blade channels at different positions relative to the Rotor 2 leading edge. The hot-film probe measurements made in the stationary frame downstream of Rotor 2 are therefore indicative of the sensitivity to the circumferential position of entry of the Rotor 1 wake segments into the Rotor 2 blade channel.

The rotor-rotor interaction occurs across the entire span. To illustrate this, the magnitudes of the Fourier coefficients of the ensemble-averaged periodic fluctuations downstream of Rotor 2 are presented in Figure 11 for four blade passing frequencies; namely, the Rotor 2 blade passing frequency, twice the Rotor 2 blade passing frequency, the Rotor 1 blade passing frequency, and the Rotor 1-Rotor 2 difference blade passing frequency. It can be seen that for both circumferential positions across the entire span, but in particular from hub to midspan, the coefficients at the Rotor 1 blade passing frequency are second in magnitude only to the coefficients at the Rotor 2 blade passing frequency. Measured in terms of relative influence, i.e., comparing the magnitudes of the coefficients at the Rotor 1 blade passing frequency to the magnitudes of the coefficients at the Rotor 2 blade passing frequency, the effect of the Rotor 1 exit flow onto the Rotor 2 flow is stronger at Position B than at Position A. The strongest influence is noted at Position B and 30% span where the magnitude of the coefficient at the Rotor 1 blade passing frequency attains 60% of the magnitude of the coefficient at the Rotor 2 blade passing frequency. It can furthermore be seen that the magnitude of the coefficients at the Rotor 1-Rotor 2 difference frequency is smaller at most spanwise locations than the magnitude of the coefficients at the Rotor 1 blade passing frequency.

The different influence of the Rotor 1 flow onto the Rotor 2 flow is the result of the Stator 2-Rotor 2 interaction, for the two measurement positions downstream of Rotor 2 were selected such that their distance in circumferential direction equaled a multiple of the Sta...
for a more detailed discussion of the phenomena associated with rotor-rotor interaction, the ensemble-averaged periodic and turbulent fluctuations at Position B and 30% span, i.e., the location of strongest interaction, are presented in Figure 12. Regarding first the periodic fluctuations, it can be seen that the velocity deficit in the Rotor 2 wakes varies from 5% to 25% of the mean velocity. It can further be seen that the trace of the periodic fluctuations is almost symmetric about the instant of time at which the periodic fluctuations are smallest. This is to say that the periodic fluctuations increase in the first half of the interaction cycle in almost the same manner as they decrease in the second half of the interaction cycle. The interaction cycle denotes the period of time a stationary observer watches elapse between recurring identical positions of the Rotor 1 blades to the Rotor 2 blades and is defined to start at the instant of time when the smallest periodic fluctuations occur. Note that since the difference in blade number between the two rotor blade rows is two, a stationary observer will watch identical positions of the Rotor 1 blades to the Rotor 2 blades twice per rotor revolution; therefore, for Rotor 1 and Rotor 2 the interaction cycle is half as long as the time required for one rotor revolution. Turning next to the turbulent fluctuations, a peculiarity is observed around the instant of time with the smallest periodic fluctuations - a second peak per rotor blade passing period appears in the turbulent fluctuations, in addition to the one peak that identifies the increased turbulence levels of the Rotor 2 wake. This second peak is most pronounced in the sense of being equal in magnitude to the peak associated with the Rotor 2 wake when the periodic fluctuations are smallest. It can be discerned in the turbulent fluctuations for about 16 blade passing periods (of one interaction cycle) from approximately 4 blade passing periods prior to the occurrence of the smallest periodic fluctuations to approximately 12 blade passing periods thereafter.

The unfolding of this second peak is best illustrated by regarding a contour plot of the turbulent fluctuations downstream of Rotor 2, Figure 13. Presented are the turbulent fluctuations corresponding to the first 25 blade passing periods of the traces of the periodic and turbulent fluctuations shown in Figure 12. Note that a stationary observer downstream of a turbine blade row will see the rotor exit flow filament following order suction side flank of the rotor wake, rotor wake, pressure side flank of the rotor wake, and finally the rotor core flow. Furthermore it has to be kept in mind that for a stationary observer the circumferential position of entry of the Rotor 1 wake segments into the Rotor 2 blade channel will shift cyclicly from the pressure side of the blade leading edge to the center of the blade channel, then to the suction side of the blade leading edge, and finally back to the pressure side of the blade leading edge (cf., Figure 10). The contour plot shows clearly the large turbulent fluctuations in the endwall regions that are ascribed to the rotor secondary flows. Turning the attention to the region extending from 20% to 60% span (where the secondary flow influence was presumed small) a "normal" rotor exit flow structure, i.e., high turbulence levels during the rotor blade passing period identifying the rotor wake low and high turbulence levels identifying the rotor core flow, is observed for the first 3 blade passage periods. During blade passage periods 4 to 6 ramification of rotor wake fluid happens at midspan. Next, the point of ramification moves gradually closer to the hub. At midspan, the branch of highly turbulent fluid (compared to the core flow turbulence level) moves away from the pressure side flank of the Rotor 2 wake, rotor blade passing periods 7 to 9. This gradual moving away from the pressure side flank of the Rotor 2 wake strongly suggests that this branch of highly turbulent fluid identifies the Rotor 1 wake segments. This is to say that as the position of entry of the Rotor 1 wake segment into the Rotor 2 blade channel shifts from the pressure side of the blade leading edge to the center of the blade channel, the fluid of rather high turbulent fluctuations associated with the Rotor 1 blade segments separates from the Rotor 2 wakes, and is found in the blade channel center between two rotor blades. Another few blade passing periods later, blade passing periods 10 to 18, the branch of highly turbulent fluid, i.e., the Rotor 1 wake fluid, in the center of the Rotor 2 blade passage has completely separated from the pressure side flank of the Rotor 2 wake. It has also moved closer to the suction side flank of the Rotor 2 wake. At this instant of time, a double-peak structure occurs in the traces of the turbulent fluctuations from 30% span to 50% span, as was exemplarily shown for 30% span. During the next few blade passing periods, the lump of turbulent fluid in the center of the blade passage gradually merges into the suction side flank of the Rotor 2 wake, and the double-peak structure in the trace of the turbulent fluctuations diminishes.

The contour plot of the turbulent fluctuations clearly shows that blade passage periods exist with Rotor 1 wake segments not having merged into Rotor 2 wakes. Therefore, the second peak in the turbulent fluctuations has to be ascribed to Rotor 1 wake segments that are convected through the Rotor 2 blade channel without merging into the Rotor 2 wakes. This analysis of the contour plot of the turbulent fluctuations downstream of Rotor 2, in conjunction with the corresponding traces of the turbulent and the periodic fluctuations, elucidates that the downstream rotor-rotor interaction is indeed a wake-induced interaction.

Returning to the analysis of the turbulent fluctuations at 30% span, Figure 12, it can be seen that the trace of the turbulent fluctuations, in contrast to the trace of the periodic fluctuations, is not symmetric about any point of time. In the first half of the interaction cycle, the turbulence levels in the Rotor 2 wakes increase gradually from their lowest value attained when the periodic fluctuations are smallest to their highest value attained when the periodic fluctuations are largest. The core flow turbulence levels during this first half of the interaction cycle, however, first decrease gradually before increasing markedly. For the second half of the interaction cycle, the turbulence levels in the Rotor 2 core flows first continue to increase and then remain almost constant. Hence, the turbulence levels in the Rotor 2 core flows are higher in the second half of the interaction cycle than in the first half of the interaction cycle. The turbulence
levels in the Rotor 2 wakes during the second half of the interaction cycle gradually decrease from their maximum level to their minimum level attained at the end of the cycle.

In interpreting the data, it is important to assess correctly the circumferential position at which the Rotor 1 wake segments that can be discerned in the turbulent fluctuations downstream of Rotor 2 enter the Rotor 2 blade channel. Since these wake segments had clearly not merged with the Rotor 2 wakes they were inferred to have entered the Rotor 2 blade channel somewhere near the center. Thus, the measurements during the first half of the interaction cycle indicate the response of the Rotor 2 boundary layers to the Rotor 1 wake segments as the position of entry of these wake segments shifts from the center of the Rotor 2 blade passage to the Rotor 2 leading edge, whereas the measurements during the second half of the interaction cycle indicate the response of the Rotor 2 boundary layers to the Rotor 1 wake segments as the position of entry of these wake segments shifts from the Rotor 2 leading edge to the center of the blade channel. Therefore, during the first half of the interaction cycle, the blade suction side boundary layer will be affected by the Rotor 1 wake segments, whereas during the second half of the interaction cycle the blade pressure side boundary layer will be affected by the Rotor 1 wake segments. This may explain the greater variations of the turbulent fluctuations observed during the first half of the interaction cycle, for wake-induced transition has been observed to significantly affect the suction side boundary layer of blade rows operating in the Re number regime typical for low-pressure turbines (Schröder, 1990, and Hodson and Addison, 1989) However, this analysis does not help fathom why a strong sensitivity to the position of impingement of the Rotor 1 wake segments upon Rotor 2, similar to the one observed in the turbulent fluctuations, is not observed in the periodic fluctuations.

CONCLUSION

Hot-film probe measurements were made downstream of every rotor blade row of a five-stage low-pressure turbine to investigate unsteady flow phenomena in multistage low-pressure turbines. Rotor-rotor interaction and stator-rotor interaction were observed to have a profound influence on the flow through the turbine. Interaction of rotors of different turbine stages occurring owing to the influence the wakes shed by one rotor blade row exerted on the flow through the next downstream rotor blade row. This wake-induced rotor-rotor interaction resulted in strongly amplitude-modulated periodic and turbulent velocity fluctuations downstream of every rotor blade row with the exception of the most upstream one. Significantly different wake depths and turbulence levels measured downstream of every rotor blade row at circumferential positions apart a multiple plus one half of the spacing of the immediate upstream stator blade row evidenced the effect of the circumferentially nonuniform stator exit flow upon the next downstream rotor blade row. The variation in time of the velocity deficit in the wakes downstream of Rotor 2 owing to rotor-rotor interaction during one rotor revolution was found to be comparable to the variation in space of the velocity deficits in the wakes downstream of Rotor 1 owing to stator-rotor interaction. Therefore, stator-rotor and rotor-rotor interaction were observed to be of comparable significance to the flow through this multistage turbine. Stator-rotor interaction also strongly influenced the overturning and the underturning of the rotor wakes, caused by the rotor secondary flows, in the rotor endwall regions. Low rotor wake overturning and underturning, i.e., reduced rotor secondary flow influence, were observed to correlate well with low rotor wake turbulence levels.
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