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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Institute of Hydromechanics, National AS as follows: The contractor will perform experimental investigation of a large-scale vortical structure in boundary layers over turbine blades. The research is to be performed at the Propulsion Directorate of Wright laboratory in Dayton, Oh.

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REPORT

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FLOW CONTROL AROUND TURBINE BLADES USING CENTRIFUGAL INSTABILITY ANALYSIS

Introduction

The work in the frame of the Contract F61708-97-W0229 was planned as a current research activity in the field of mutual interest and as the development of the background for the future collaboration. Therefore an objective was defined by the prospects of the long-term cooperation dealt with the fundamental studies of the boundary layer development and control, as well as the application of this basic knowledge for present technological needs in turbomachinery..

In this connection, the analysis was made of available research potential of both sides and formerly obtained results together with the priority areas where joint efforts could be supplementary and effective. It was found, in particular, that no special investigations related to the design of low pressure turbine blades were carried out. This design repeats one for the high pressure case and therefore is far from being optimal for given flow conditions. Most serious consequences of this disagreement between the blade geometry and flow conditions of their exploitation are connected with the boundary layer separation at a suction side of the blade which typically happens at the position of 10% of the chord (Ref. 1, 2). Since the low pressure turbines operate at relatively low Reynolds numbers in the turbulent environment, their work optimization should be based on the boundary layer control techniques using the available experience (Ref. 3,4).

As a result, it was concluded that the joint research work must be mutually interesting and advantageous. It can bring together different approaches and experience, stimulate the insight into the vortex dynamics mechanisms of flows affected by body forces (centrifugal forces and buoyancy) that, in its turn, will help to solve technological problems dealing with optimization of performance and operation of low pressure turbine blades.

The objective was formulated as follows:

Examination of a boundary layer structure over turbine blades taking into account centrifugal effects; application of this actual information to develop recommendations related to generation and maintenance of a vortical flow structure that is optimal from the viewpoint of hydraulic losses, especially because of the early boundary layer separation.

Being formulated in terms of fundamental research, the investigation must be a study of the receptivity problem, i.e. the study of a boundary layer response type to controlled excitation. In their applied interpretation, the results, must constitute the basis for further investigation directed to formulation of recommendations to control a boundary layer over a concrete turbine blade. Generally, these recommendations should concern both the suction, and pressure sides of the blade; they should take into consideration possibilities to modify both a blade shape, and its surface using special techniques (e.g. riblets or organized surface roughness) which should stimulate and maintain the favorable boundary layer vortical structure to delay flow separation on the suction side.

Background

Flow geometry over a blade defined by the varying surface curvature of both signs, stipulates the studies of boundary layers effected by centrifugal forces or, for a more general case, by body forces (centrifugal forces and buoyancy due to the flow-blade temperature difference). The state of the arts of the problem supposes its development for the turbine blade application using traditional approaches based, for instance, on the Goertler stability of boundary layers over concave surfaces (Ref. 5-10) plus that in thermally stratified flows.
Another, more general approach, quite different from the known stability theories, may naturally account for a combined effect of any body forces in a flow, was proposed recently (Ref. 11, 13).

All the studies refer to an experimental evidence of streamwise counter-rotating pairs of vortices naturally developed in various flows with available body forces. On the one hand, diversity of situations where streamwise vortices are observed supposes the existence of a certain universal mechanism of their formation and behavior (defined by the interaction of viscous and body forces in boundary layers) that inevitably results in the development of elongated vortical structures (Ref. 11, 12). On the other hand, streamwise vortices due to their regular deterministic character, may give a key to effectively control vortex dynamics and subsequently be used as a tool or basic structure in a boundary layer to be maintained and manipulated with using various techniques. In particular, they were shown to be helpful to delay or prevent the boundary layer separation under conditions of an adverse pressure gradient downstream of the flow (Ref. 15).

Theoretically (E.Nikiforovich, Ref. 13, 14) the mentioned new approach is based on the asymptotic analysis of full Navier-Stokes equations using a small parameter explicitly depending on body forces. In case of centrifugal forces only, it is

$$\varepsilon = \mathbf{Re}_R^{-1},$$

R is the curvature radius,
$\mathbf{Re}_R$ is the Reynolds number based on radius.

This analysis has given the estimates for spatial-temporal vortical scales in a boundary layer through the basic flow parameters (it represents a new result compared to the traditional approaches). It was shown that longitudinal vortices as an essential flow structural feature originate from the interaction of two vorticity sources (due to viscous and body forces) when their intensities become comparable at a certain downstream distance,

$$x_0 = A\,R\,Re_R^{-1/3}$$

with a minimum space scale in normal and spanwise directions,

$$L_0 = R\,Re_R^{-2/3}.$$

Experimental results obtained for a transitional boundary layer over concave surfaces (N.Yurchenko) match both theoretical approaches proving the validity of the new one and clarifying physical mechanisms and meanings of theoretically deduced values (Ref. 12).

Work content

The work was carried out using research facilities of the Wright-Patterson Lab, Turbine Engine Division; the results obtained for low pressure turbine blades having been analyzed in the frame of traditional and recently developed theories.

Since the fluid motion around a turbine blade can be specified as a turbulent flow effected by centrifugal forces and buoyancy, it was important to know both turbulent characteristics of the flow, and its particular features induced by temperature gradients with the main flow, surface curvature and roughness. Therefore the first stage of the work consisted in the analysis of the flow geometry around the blade and turbulent spectra of the flow using the results of previous measurements.

The geometry of the flow was defined by the blade shape and the main flow parameters:
for the pressure surface, the curvature radius was changing from the leading edge (R=1/16"-1/4") through R~1" to the aft (R=12"); the cord Reynolds numbers were within Re_C=50,000-300,000, typically about 100,000. Liquid crystal visualization showed streamwise vortices, or a finger-type flow structure, with the space scale λ_z=0.8 mm observed over the concave (pressure) side of the blade at Re_C=67500 in the range of $x_0/c \approx 0.2-0.7$ (chord, c=7").

These experimental results were processed and analyzed, first of all, in the frame of the mentioned (Ref. 13, 14) theory which gave vortical structure characteristics near the wall through the basic flow parameters (free-stream velocity U_0, curvature R^{-1}, and kinematic viscosity ν).

(1). The x_0/c value, nondimensional downstream distance where the streamwise vortices may appear under given experimental conditions, was checked for 3 cases of curvature radius supposing Re_C = 100,000:

1. R=0.7", and found x_0=0.3", x_0/c=0.04;

2. R=5.0", x_0=1.2", x_0/c=0.17;

3. R=12.0", x_0=2.17", x_0/c=0.31,

as well as for Re_C=67500:

R=5.0": x_0=1.4", x_0/c=0.2;

R=7.0": x_0=1.7", x_0/c=0.24.

It shows a good agreement between the results of an experiment (x_0/c=0.2) and calculations based on the theoretical formula and real flow parameters.

Since the variable curvature in a downstream direction complicated the determination of an exact value of the radius at $x_0/c \approx 0.2$, the inverse calculation was made: the radius was estimated from the known other parameters (Re_C=100,000;

c=7"; universal constant A=10, found from known other experimental results) using the formula $\mathbf{x_0 = A\, R\, Re_R^{-1/3} = A\, R\, Re_C / c\, R^{-1/3}}$.

R was found to be about 5", having been a very realistic value, i.e. the curvature value causing centrifugal forces which result in the formation of streamwise vortices at a downstream position corresponding to the experimental one.

(2). As it was mentioned above, rough experimental estimates of a spanwise wavelength of the observed vortical structure gave a value of λ_z=0.8 mm (Ref. 1, 2). According to the theoretical analysis by Nikiforovich, $\lambda_z=8L_0$ where L_0 is a vortex space scale normally to the velocity vector. Besides, comparison and interpretation of the data in the frame of the Goertler stability theory showed a good agreement with the traditionally used wavelengths of streamwise vortices in a spanwise direction having given a corrected relationship, $\lambda_z=9L_0$, (Ref. 13).
Therefore the scales of the streamwise vortical structure defined by the basic flow parameters $\mathbf{L_0 = R\, Re_R^{-2/3}}$ were calculated and found to be

L_0=0.1mm for R=5", Re_C=67,500;

L_0=0.09 mm for R=5", Re_C=100,000;

L_0=0.12 mm for R=10", Re_C=67,500,

what is in a good agreement with the value of λ_z=0.8 mm observed experimentally in the boundary layer of a turbine blade.

(3). The known Goertler stability diagram (e.g., see Ref. 6-10) is very demonstrative in relation to the amplification rates of streamwise vortices with various scales which evolve in boundary layers depending on the Goertler number $\mathbf{G = U_0\, \delta_2^{3/2}\, \nu^{-1}\, R^{-1/2}}$. Vortices described by the nondimensional wave length
$\Lambda = \lambda_z^{3/2}\, \mathbf{U_0} / \nu\, \mathbf{R^{1/2}} \approx \mathbf{39}$, are neutral, i.e. have a zero amplification rate for a wide range of Goertler numbers. Larger scale vortices are described in the Goertler diagram by the straight lines $\Lambda = \mathbf{const} > \mathbf{39}$. In this connection it was interesting to check where the experimentally observed vortices can be found on the diagram. This estimation was made for the 8 mm scale vortices following $\Lambda = \lambda_z^{3/2}\, \mathbf{Re_C / c\, R^{1/2}}$:

for R=5", Re_C=67,500 it was found that $\Lambda = 24$;
for R=5", Re_C=100,000 -- $\Lambda = 36$.

It means that the streamwise vortical structure registrated in the boundary layer of a low pressure turbine blade is of a neutral type, i.e. neither amplifying, nor decaying in a downstream direction. This flow structural feature can be used to maintain a necessary thermodynamical balance in a boundary layer using one or another method of the boundary layer control. For instance, artificial generation of longitudinal vortices was shown to delay flow separation over a surface with an adverse pressure gradient (Ref 15). In this connection, recommendations were made concerning a method and a technique of the boundary layer control over a tested turbine blade.

Summary

The formulated purpose and program of the Contract F61708-97-W0229 yielded the following work fulfilled and the results obtained:

1. Analysis was made of available experimental results obtained in the WL, Turbine Engine Division, dealt with the measurements of velocity and temperature fields around a turbine blade; it helped to formulate in more detail the subject of investigations.

2. Space scales of the vortical structure developing over a concrete turbine blade under given test conditions were calculated using a theory by E.Nikiforovich (Hydromechanics Institute,

Kiev) for boundary layers effected by body forces. These results showed a good agreement with the experimentally obtained data.

3. Interpretation of the experimental results was given from the comparison of calculated and experimentally observed scales of longitudinal vortices dominating in the boundary layer over a curved surface. To reveal physical mechanisms of the vortex dynamics over the turbine blade, Goertler stability analysis was attracted that showed a neutral character of regular vortices practically arising in a boundary layer.

4. The boundary layer control method was proposed to delay flow separation on a suction side of a turbine blade using a special construction of the blade surface layer which should stimulate the development of streamwise vortices in a boundary layer with the scale and properties corresponding to requirements of the flow optimization.

The work in the frame of the Contract displayed the problems of primary interest that can be solved more efficiently using joint efforts and, in particular, the experience and research potential of the Ukrainian side. Continuation of the work should transfer the basic knowledge of the vortical structure development under body forces into applications dealing with the optimization of a turbine blade operation. In this connection, the program was discussed and formulated as a proposal for a future joint project
"Studies of centrifugal/Buoyancy Effects and Receptivity of Boundary Layers Applied to the Optimization of Turbine - Blade Performance"..

Prospects; research program

Further research must bring an insight into the mechanisms of the flows developing under buoyancy or both buoyancy, and centrifugal forces, i.e. under conditions of turbine blades operation at low Reynolds numbers.

This basic knowledge is to be applied for finding efficient methods of the boundary-layer control to minimize hydraulic losses or to enhance heat transfer near the turbine blade surfaces what should result in the improvement of the turbine blades performance. In particular, the program of prospective investigations should include the following issues:

1. similarity between boundary-layer flows effected by buoyancy and centrifugal forces, i.e. between flow structure over heated/cooled and curved walls;
2. receptivity to external disturbances (distributed surface roughness, regularly spaced roughness elements, riblets, free-stream turbulence);
3. determination of a spatial scale of streamwise vortices aimed to delay flow separation on a suction side of a turbine blade;
4. choice of optimal ways of boundary-layer control based on the knowledge of vortex dynamics and receptivity studies (generation and maintenance of a suitable vortical structure);
5. design of a vortex-generating device;
6. downstream location(s) of vortex generators on the turbine blade surface;
7. recommendations related to the improvement of the blade shape (estimates of the curvature favorable from the viewpoint of optimization of hydraulic losses and heat transfer).

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