Unsteady Flows and Forces by Turbine Rotor-Stator Interactions*

Tetsuo NISHIYAMA**

With the urgent demand for higher performance in axial turbines, the unsteadiness induced by the mutual interactions between the nozzle and rotor cascade rows has attracted much attention. As the number of published papers on this topic has recently increased considerably, the present state of research is reviewed here under four categories. This report might be expected to deepen our understanding of the unsteadiness within the turbine stages and also to provide some suggestions for further research in this field.

Key Words : Unsteady Flow, Cascade, Rotor-Stator Interaction, Boundary layer, Fluctuating Fluid Forces, Sinusoidal Gust, Resonant Response, Coupled Bending-Torsion Oscillation

1. Introduction

In axial flow gas and steam turbines, there exists an inevitably relative movement in circumferential direction between the nozzle guide vane and the rotor blade cascade rows arranged in a short axial gap. Unsteady perturbed flows are seriously induced on the blade surface and within the rotor passage by the strong mutual interactions between rows, and space and time fluctuations result directly in blade vibrations, noise generation and significant causes of flow energy loss.

In connection with the recent conspicuous trend toward high aerodynamic, thermal and structural performance of axial turbines, demand is focused on the prevention of blade vibration and fatigue, reduction of blade noise generation, prediction of blade

surface temperature and maintenance of safely normal operations in nonuniform inlet flows. Hence the unsteady flows induced by the nozzle guide vane and rotor blade cascade rows have recently attracted strong interest, and many investigations have been actively carried out from both theoretical and experimental standpoints. Useful and valuable conclusions which might be important guides to future research can be found in many of the papers published.

2. Unsteady Boundary Layer Flow on the Rotor Blade Surface

2.1 Boundary layer

The transition behaviour of the boundary layer on the rotor blade surface seriously influences heat transfer performance and additional generations of flow energy loss.

In simulating the effects of the viscous wake, a single aerofoil is traversed in front of the turbine cascade. Both the axial distance between the aerofoil and the cascade and the position in the circumferential direction are changed in discrete steps⁽¹⁾. Strong

*Received 20th November, 1989

**Department of Mechanical Engineering, Faculty of Science & Engineering, Ishinomaki Senshu University, Ishinomaki, Miyagi, 986, Japan

correlations can be clearly seen; the heat transfer coefficient increases significantly in the regions of high turbulence intensity along the cascade aerofoil surface. Particularly, it is shown that the turbulence intensity and also the heat transfer coefficient become notably large in the frontal part on the face due to the viscous wake effect and also in the vicinity of the leading edge on the back by the effects of both the viscous wake and the boundary layer transition.

The effects of the viscous wake shed by an upstream moving circular cylinder on boundary layer transition on the downstream rotor blade surface are examined by measurements of the time mean and unsteady heat flux along the rotor surface in the cascade⁽²⁾. The time mean heat flux distributions in the frontal part on the back are shown for both cases-without and with the wake effects in Fig. 1. In the natural transition, the boundary layer flow on the back is laminar and turbulent for freestream inlet flow of turbulence intensity 2 % and 5 %, respectively. The time mean heat flux of the latter is two or three times the former. However in the forced transition by the wake effect, the time mean heat flux increases significantly and then approaches one for the turbulent boundary layer in the natural transition in the rear part on the back. The time fluctuation of the unsteady heat flux over one period in the frontal part of the

Fig. 1 Effect of wake passing on mean heat flux to laminar and turbulent boundary layer⁽²⁾, (Linear cascade; pitch-chord ratio 0.875, stagger angle 35°)

back is shown in Fig. 2 for both cases-without and with the wake effect. In the former, the natural transition begins to occur at site 6, and then the boundary layer flow becomes fully turbulent at site 10 by the convection and then growth of the turbulent patches generated in the boundary layer. However, in the latter, the turbulent patches induced by the wake effect are convected downstream while growth proceeds, and finally the boundary layer flow becomes turbulent at site 4. The boundary layer flow once again becomes laminar somewhat later after the wake has passed away. The convection velocity of the turbulent patches in the boundary layer is shown to coincide favourably with that of the convected viscous wakes on the rotor blade surface within the passage. Further it is clearly verified that the unsteady heat flux distributions on the back can be successfully predicted by the proposed numerical model for generation and convection of the turbulent patches⁽³⁾.

Based on the unsteady measured data of the heat transfer rate distributions on the rotor blade surface of the transonic cascade, the essential effects of the shock wave and its connection with the viscous wake by the moving circular cylinder on the rotor blade boundary layer are examined in some detail^{(4),(5)}. The mean heat transfer rate is substantially decreased in the after part on the back by the impinged shock wave and also in the greater part of the back by the viscous wake, which makes the effective incidence smaller. On the other hand, the increase of the unsteady heat transfer rate by the shock wave and viscous wake overrides the decrease by the reduced effective inci-

Fig. 2 Relief plot of normalised heat flux for freestream of low turbulence 2 % (upper) and wake passing (lower)⁽²⁾, (Linear cascade; pitch-chord ratio 0.875, stagger angle 35°)

dence. Particularly, the important role of the shock wave is pointed out; the abrupt fall in unsteady heat transfer rate can be attributed to a transient separation caused by the shock wave, followed by a very fast transient spike as the boundary layer reattaches turbulently. As shown in Fig. 3, after the shock wave impinges at site 6 on the back and then propagates upstream, the laminar boundary layer separates instantly extremely near the leading edge but reattaches turbulently at site 4. Hence the unsteady heat transfer rate suddenly rises in a sharp peak due to the turbulent patches generated. The boundary layer flow once again becomes laminar after the turbulent patches are convected away downstream. Somewhat later, the unsteady heat transfer rate again increases in a square type peak by arrival of the viscous wake. The increase of the unsteady heat transfer rate can be

Fig. 3 Effects of wakes and shock waves on heat transfer⁽⁵⁾ (Transonic linear cascade; pitch-chord ratio 0.863, stagger angle 30°)

seen in site 1 only by the viscous wake, but in site 11 by both the viscous wake and shock wave. No effects of the shock wave can be found downstream from site 11 on the back as well as throughout the face. The time responses of the boundary layer to shock wave and viscous wake are shown in Fig. 4; the convection velocity of the leading edge of the turbulent patches is found to be about 0.8 times the freestream velocity, whereas the velocity of the trailing edge is about 0.6 times the freestream velocity. This shows that the transient spike in the unsteady heat transfer rate is produced by means of a turbulent patch remaining in the boundary layer after the collapse of the separation. The later arrival of the wake causes a characteristic square-wave type transition from laminar to quasisteady turbulent flow and then the aforementioned reversal to laminar flow. The convection velocity of the trailing edge of the wake-generated turbulent patch is about 0.5 times the freestream velocity, but one of the leading edge seems to be nonuniform.

Fig. 4 Time response of boundary layer to shock and wake⁽⁵⁾ (Transonic linear cascade; pitch-chord ratio 0.863, stagger angle 30°)

2.2 Surface pressure distribution

Extensively measured data of the surface pressure and heat transfer coefficient distributions on the midspan of the stator-rotor blade for a large scale axial turbine of single stage are presented and then the boundary layer behaviour on the stator and rotor is examined in detail⁽⁶⁾. Tollmien-Schlichting waves are found in the boundary layer at site 4 and the boundary layer is turbulent at site 5 on the stator back. On the other hand, the laminar boundary layer at site 7 on the rotor back is forced to be turbulent at every impingement of the upstream wake. Hence the periodic oscillations between laminar and turbulent boundary layer flow on the rotor back surface are in agreement with similar observations. The amplitude of the unsteady surface pressure is shown in Fig. 5 on the upstream stator and downstream rotor. The amplitude on the stator is minimum at sites 4 and 11 and maximum at site 8. The downstream rotor exerts influence at site 5 on the stator, which is located at the throat of the stator passage, and then the induced unsteady pressure propagates up-and downstream from there. The phase changes violently as the trailing edge is approached and also is nearly the same in sites 2-4 as in sites 12-15 because of being located at both sides of the channel when viewed as a channel. On the other hand, the amplitude on the rotor is maximum at sites 10 and 5, although the former is much larger than the latter and decreases gradually to the trailing edge. Since the viscous wake of the upstream stator wholly covers the rotor surface at the instant when the aft stagnation streamline of the stator comes to be on the same line as the fore stagnation streamline of the rotor, the phase of sites 2-4 on the stator is almost the same as that of sites 5-9 on the

Fig. 5 Amplitude of unsteady surface pressure on the stator and rotor blade⁽⁶⁾ (Rotor blade : axial gap ratio 0.1, stator-to-rotor pitch ratio 1.27, rotor passing frequency 16.18)

rotor.

3. Wake-Generated Unsteady Flows inside the Rotor Passage

3.1 Single stage

The time mean and unsteady velocity within the passage are measured circumferentially at the midspan of the rotor blade for the single stage axial turbine⁽⁶⁾, and then the three dimensionality and un-

Fig. 6 Time mean absolute inflow velocity, inflow angle and pitch angle at station 3⁽⁷⁾ (Rotor blade : axial gap ratio 0.1, stator-to-rotor pitch ratio 1.27, rotor passing frequency 16.18)

steadiness in the perturbed flow field are examined in detail. The circumferential distributions of the time mean and unsteady absolute inflow velocity, inflow angle and pitch angle are shown in Figs. 6 and 7, respectively. Within the convected viscous wake, these time mean properties do change periodically with the rotor passing frequency, and both the inflow velocity and inflow angle are smaller and the radial velocity is inward compared with those outside the wake. Moreover, inside the convected wake, the random unsteadiness is notably larger, and on the other hand, the periodic unsteadiness is smaller compared with those outside the wake. Furthermore, the circumferential variations are more significant on the back for the former and on the face for the latter⁽⁷⁾.

It is clearly shown that the random unsteadiness considerably increases within the incoming viscous wake immediately after being cut off by the moving rotor blade, and a pair of vortices can be found contra-rotating in the convected wake inside the rotor passage⁽⁸⁾. The time mean relative inflow velocity and angle are shown at stations 1 and 2 in Fig. 8. Since the relative inflow velocity is smaller and the inflow angle is larger in the wake within the rotor passage, the slip

velocity is induced within the wake and directs to the back side from the face side, as clearly shown from the velocity vector diagram. Further, the fact that the relative inflow angle is larger in station 2 than in station 1 shows that the wake is deformed into a bow shape while being convected downstream inside the rotor passage.

From the extensive measurements of the unsteady velocity and turbulent intensity, the dynamic behaviour and deformations of the convected wake inside the rotor passage-cutting, migration, bowing and shearing—are shown to be interpreted physically and reasonably well understood, and particularly, the negative jet is shown to be clearly distinguished inside the wake⁽⁹⁾. These are schematically illustrated in Fig. 9. Moreover, an inviscid analytic model is also proposed for the deformation and convection of the incoming wake inside the rotor passage⁽¹⁰⁾.

It is verified experimentally that the secondary vortices inside the stator passage are located very close to the viscous wake shed by the stator row, and then, in the downstream rotor entrance region, the turbulence increases above the levels in the incoming wake but only in the area associated with the stator

Fig. 7 Random and periodic unsteadiness at station 3⁽⁷⁾ (Rotor blade : axial gap ratio 0.1, stator-to-rotor pitch ratio 1.27, rotor passing frequency 16.18)

Fig. 8 Relative flow velocity and angle within the rotor passage⁽⁸⁾ (Rotor blade : axial gap ratio 0.89, stator-to-rotor pitch ratio 1.5, rotor passing frequency 12.16)

Fig. 9 Schematic illustrations of the deformations of wake (left) and contra-rotating vortex motion within the rotor passage (right)

secondary vortices. The reasonable explanation of this phenomenon is that the vortices break down and some of their kinetic energy is converted into turbulence⁽¹¹⁾. Furthermore, this augmented turbulence has a close relationship not only with the generation of the unsteady flow energy loss but also with the boundary layer growth, heat transfer performance on the rotor blade surface and the secondary vortices in the rotor passage⁽¹²⁾.

A time marching calculation is made for the unsteady flow generated by the interaction of the upstream wakes with a moving rotor blade row. The inviscid equations of motion are solved using a finite volume technique. The results confirm the existence of such phenomena as wake chopping, migration and shearing. As shown in Fig. 10, the predicted and measured unsteady blade surface velocities on the rotor at the midspan section are reasonably comparable, and the maximum unsteady surface pressure on the back occurs almost at the center of the impinging wake, which gives definite evidence of the existence of the negative jet^{(13),(14)}.

3.2 Multistages

Measurements of the radial and circumferential distributions of the turbulence intensity are made within the rotor passage of the five stage axial turbine⁽¹⁵⁾. A strong interaction is identified between two successive rows of rotor blades; that is, the main parameter is the nonuniformity of the flow entering the downstream blade row. Dynamic separation

occurs when the wake of the upstream rotor blade enters the blade passage near the leading edge, preferably on the face side. The turbulence intensity of the rotor downstream is augmented when the wake of the upstream rotor blade enters the middle of the rotor blade passage.

4. Unsteady Fluid Forces by Mutual Interactions

4.1 Unsteady forces by the potential flow interaction

The unsteady surface pressure distributions on the profile and the unsteady fluid forces are obtained by somewhat simplified method of analysis that makes the unsteady bound vortex distribute on the profile contours of the nozzle and rotor cascades, and the free vortex distribute only on the steady stagnation streamline from the trailing edges confined to the range of the axial gap⁽¹⁶⁾. The instantaneous local positions of the free vortex shed from the trailing edges cannot be determined in advance, and so the problem of determining the unsteady bound vortex distributions is of inherent nonlinearity. By the time marching method, which makes the free vortex shed from the trailing edge at each time step and continues the numerical process until the periodicity of the blade passing frequency is fully accomplished in a whole flow field⁽¹⁷⁾, the instantaneous positions of the free vortex downstream from the trailing edges of both the nozzle and rotor cascades and the time fluctuations of

Fig. 10 Comparisons of predicted unsteady surface velocities (upper) with measured ones (lower)⁽⁹⁾ (Rotor blade; axial gap ratio 0.534, stator-to-rotor pitch ratio 1.42, Rotor passing frequency 4.5)

Fig. 11 Potential interaction; instantaneous positions of free vortex (upper) and axial and circumferential components of unsteady force (lower)⁽¹⁷⁾ (Linear cascade; axial gap ratio 0.125, stator-to-rotor pitch ratio 2, rotor passing frequency 11.52)

the unsteady fluid forces are shown in Fig. 11; the amplitude of the circumferential component is considerably larger in the rotor cascade but almost comparable in the nozzle cascade, compared with that of the axial component. Also, both components in the nozzle cascade are larger than those in the rotor cascade.

Through numerical analysis by means of Gile's program, the potential flow interaction effects on the unsteady pressure field and fluid forces are obtained⁽¹⁸⁾; it is pointed out that the significant effects can be clearly seen only in the flow field near the rotor leading edge for low stator-to-rotor pitch ratio but wholly in the rotor passage for large stator-to-rotor pitch ratio.

Three dimensional numerical analysis by the finite volume method is presented for the transonic axial turbine, and then the unsteady surface pressure distributions on the rotor blade and flow angle distribution within the rotor passage are examined⁽¹⁹⁾.

4.2 Unsteady forces by the viscous wake interaction

The viscous wakes of the nozzle cascade row are generally regarded as the inviscid circumferentially sinusoidal gust, and its amplitude is duly treated as being infinitely small compared with its wavelength, which is equal to the nozzle cascade pitch. On the other hand, the steady loading of the turbine rotor blade is relatively large and so may be regarded as being of finite order of magnitude. Hence the perturbed unsteady quantities induced by the interaction of the incoming sinusoidal gust with the turbine rotor blade come to be of an infinitely small order of magnitude. In this point, we can find feature inherent to the turbine rotor blade for the unsteady fluid forces.

The unsteady fluid forces of the rotor cascade moving in the sinusoidal gust are analysed by the singularity method, which can take account of the flow vorticity⁽²⁰⁾. The rotational component of the perturbed unsteady velocity on the rotor surface and also the equi-vorticity lines inside the rotor passage are shown in Fig. 12. Within the rotor passage, the rotational velocity is ripped inward on the face and splayed out on the back in the crest of the convected gust denoted by the full dotted lines; the reverse is the case in the hollow of the convected gust denoted by the fine dotted lines. Further, its amplitude becomes larger in the rear part on the rotor surface. These show clearly the existence of the negative jet flow inside the wake and the circulatory vortex motion inside the rotor passage. Further, after being cut off by the rotor, the equi-vorticity lines are distorted into bow-like configurations inside the passage, and also, considerable shearing can be found downstream of the rotor cascade row^{(8),(9)}. Compari-

sons of the predicted unsteady fluid forces of the first harmonic with the measured one are made in Fig. 13⁽²¹⁾; the amplitude is notably larger for the out-of-phase inflow than for the in-phase inflow. We can also see a definite tendency for the amplitude to become large and the phase to lag with the increase of the incoming gust frequency. Predicted amplitude and phase can generally be said to agree with the measured ones. Furthermore, the vorticity effects on the unsteady surface pressure distributions and unsteady fluid forces are examined in detail⁽²²⁾.

Comparisons of the measured wake-induced unsteady surface pressure distributions with the ones predicted by the finite difference method for the mass and momentum equations are made, and then the time

Fig. 12 Equivorticity lines and rotational velocity component on the rotor cascade⁽²⁰⁾
(Linear cascade; pitch-chord ratio 0.647, stagger angle 15°, gust frequency 11.62 (left))
(Linear cascade; pitch-chord ratio 0.584, stagger angle 20°, gust frequency 12.91 (right))

Fig. 13 Comparisons of predicted unsteady axial and circumferential components with the measured ones⁽²¹⁾
(Linear cascade; pitch-chord ratio 0.584, stagger angle 20°, gust frequency 12.91)

fluctuations of the unsteady fluid forces are clarified to the fourth-order harmonics⁽²³⁾.

By numerical analysis by Gile's program, the unsteady pressure field and unsteady fluid forces are obtained and particularly, since the width of the viscous wake becomes large and the significant effects by the viscous wake interaction influence the whole flow field inside the rotor passage as the stator-to-rotor pitch ratio increases, it is pointed out that the amplitude of the unsteady fluid forces comes to increase significantly for the large stator-to-rotor pitch ratio⁽²⁴⁾. Furthermore, a numerical analysis for the upstream viscous wake effect on the moving rotor cascade is presented by combining the finite element method with the finite difference one⁽²⁵⁾.

Unsteady response analysis of the turbine rotor blade to the circumferentially and radially sinusoidal gust is presented by the singularity method in which the flow vorticity can be duly taken into account⁽²⁶⁾. The vorticity effects and three dimensional effect on the flow patterns inside the rotor passage, and also the unsteady surface pressure distribution and unsteady fluid forces are examined in some detail.

Actuator disc analysis is presented for the turbine cascade in subsonic flow with periodic heat addition. Particularly, noise produced by the interactions between the entropy wave and the rotor cascade row is examined⁽²⁷⁾.

4.3 Total unsteady fluid forces by mutual interaction

By substituting the nozzle viscous wake by the contra-rotating potential vortex rows at both sides of the wake centerline, distributing the unsteady bound vortex on the profiles of both nozzle and rotor cascades and also shedding the free vortex from the trailing edge, the singularity method is developed for obtaining the unsteady fluid forces⁽²⁸⁾. Comparisons of the predicted fluid forces over one period with the measured one prove to be reasonable.

The effects of the axial gap between the nozzle and rotor cascades are of significant order of magnitude in the potential flow interaction, but only slight in the viscous wake interaction. Hence it is pointed out that the amplitude of the total unsteady fluid forces are possible to decrease by adjusting intentionally the axial gap so as to be in out-of-phase relatively⁽²⁴⁾.

Applying the finite difference method to the Navier-Stokes equation with the Baldwin-Lomax turbulence model, the unsteady surface pressure distribution on the profile of both cascades and the unsteady velocity distribution within the rotor passage are examined, though the stator-to-rotor pitch ratio is confined to one⁽²⁹⁾. Further applying the control volume method to the governing equation with a two-

equation model of turbulence, the unsteady velocity distributions inside the rotor passage and the unsteady fluid forces are obtained⁽³⁰⁾; the time fluctuation of the total unsteady fluid forces over one period is shown for the transonic turbine stage in Fig. 14 with one by the inviscid flow numerical solution. The considerable differences between both forces exist because of the viscosity effect and also the weak shock wave in the rear on the back inside the nozzle passage. Furthermore, the total unsteady fluid forces in the impulse turbine stage are measured and then considered by the hydraulic analogy in a shallow water tank⁽³¹⁾.

5. Resonant Responses of the Moving Rotor Cascade Row to Incoming Sinusoidal Gust

When the unsteady fluid forces induced by the interaction of the rotor blade with the incoming sinusoidal gust act definitely as an exciting force, the rotor oscillations can enter into the resonant condition, which has been called nozzle resonance. Studies on the rotor blade stress induced by the resonant response⁽³²⁾, the structural response of a bladed turbine disc induced by the resonant response⁽³³⁾ and the effect of the axial gap between the nozzle and rotor cascade on the resonant response by the hydraulic analogy⁽³⁴⁾ have been performed from the practical viewpoint in the turbine stage.

The singularity method is proposed for analyzing the resonant response characteristics of the moving rotor cascade in the upstream stator wake, and then the coupling of the torsional oscillation with the bending one is considered in the resonant response condition⁽³⁵⁾. The amplitudes of the torsional and bending oscillations are shown for the gust frequency in Fig. 15. The resonance can be clearly seen in the frequency not only near the inherent frequency to own mode but also near the inherent one to other mode. The amplitude is considerably larger in the former

Fig. 14 Unsteady fluid forces of transonic turbine rotor blade⁽³⁰⁾

(Transonic rotor blade : axial gap ratio 0.43, stator-to-rotor pitch ratio 1.55, rotor passing frequency 6.49)

Fig. 15 Variations of amplitude and phase with gust frequency⁽³⁵⁾
(Linear cascade ; pitch-chord ratio 0.5, stagger angle 20°, mass ratio 250, rigidity ratio 1.12, center of gravity 0.45c)

frequency than in the latter one, and the increase of the structural damping causes notably the amplitude decrease and phase lag. Further, the amplitude at the resonant condition is generally larger in torsional oscillation than in bending oscillation.

The blade-to-blade friction dampers are also discussed in terms of controlling the resonant response by non-aerodynamic means⁽³⁶⁾.

6. Conclusions

Up-to-date investigations on the unsteady flow induced by the mutual interactions between the nozzle and rotor cascade rows in an axial turbine have been reviewed under the following four categories :

- (i) unsteady boundary layer flow on the downstream rotor blade surface
- (ii) wake-generated unsteady flow inside the rotor passage
- (iii) unsteady fluid forces by mutual interactions
- (iv) resonant response of the moving rotor cascade row to incoming sinusoidal gust

These might be very instructive and useful in interpreting and predicting the unsteady flows inside the turbine stage. However, since the three-dimensional unsteady flows are inherently of very complicated nature and also of high non-uniformity, the author feels acutely that for complete and comprehensive understanding it will be necessary to further study such items as the proposal of the physical model for the complicated unsteady flows, the spanwise changes of the unsteadiness on the rotor blade, the mutual interactions between stages in a multistage turbine, the essential differences of the unsteadiness between the rotor blade and two-dimensional cascade, the

dynamic separation of the boundary layer by the mutual interactions and the effects of both Reynolds number and Mach number on unsteadiness, and also looks forward to remarkable progress in this field of study.

References

- (1) Wittig S. et al., Laser-Doppler Studies of the Wake-Effected Flow Field in a Turbine Cascade, ASME Paper 86-GT-160.
- (2) Doorly, D. J. Modeling the Unsteady Flow in a Turbine Rotor Passage, Trans. ASME, J. Turbomach., 110 (1988), p. 27.
- (3) Elagrass, J., Measurements and Modeling of the Gas Turbine Blade Transition Process as Disturbed by Wake, ASME Paper 88-GT-232.
- (4) Ashworth, D. A., Unsteady Aerodynamic and Heat Transfer Process in a Transonic Turbine Stage, ASME Paper 85-GT-128.
- (5) Doorly, D. J. and M. L. G. Oldfield, Simulation of the Effects of Shock Wave Passing on a Turbine Rotor Blade, Trans. ASME, J. Eng. Gas Turbine & Power, 107 (1985), p. 998.
- (6) Dring, R. P., Turbine Rotor-Stator Interactions, ASME Paper 82-GT-3.
- (7) Joslyn, H. D., Unsteady Three Dimensional Turbine Aerodynamics, ASME Paper 82-GT-161.
- (8) Binder, A., An Experimental Investigation into the Effect of Wakes on the Unsteady Turbine Rotor Flow, Trans. ASME, J. Eng. Gas Turbine & Power, 107 (1985), p. 458.
- (9) Hodson, H. P., Measurements of Wake Generated Unsteadiness in the Rotor Passage of Axial Flow Turbines, Trans. ASME, J. Eng. Gas Turbine & Power, 107 (1985), p. 467.
- (10) Joslyn, H. D., Inviscid Modeling of Turbomachinery Wake Transport, AIAA Paper 85-1132.
- (11) Binder, A., Unsteady Flow Interaction Caused by Stator Secondary Vortex in a Turbine Rotor, Trans. ASME, J. Turbomach., 109 (1987), p. 251.
- (12) Binder, A., Turbulence Production Due to Secondary Vortex Cutting in a Turbine Rotor, ASME Paper 85-GT-193.
- (13) Hodson, H. P., An Inviscid Blade-to-Blade Prediction of a Wake-Generated Unsteady Flow, Trans. ASME, J. Eng. Gas Turbine & Power, 107 (1985), p. 337.
- (14) Mitchel, N. A., A Time marching Method for Unsteady Two Dimensional Flow in a Blade Passage, Int. J. Heat & Fluid Flow 2-4 (1980), p. 205.
- (15) Binder, A., Turbulence Measurements in a Multistage Low Pressure Turbine, ASME Paper 88-GT-79.
- (16) Nishiyama, T. and Sasaki, M., Unsteady Forces Induced by Potential Interaction Between the Nozzle and Turbine Rotor Cascade Rows, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 460 (1984), p. 2888.

- (17) Lienhart, W., Aerodynamische Erregungskrafte von Schaufelschwingungen in Axialen Turbomachinen Infolge der Interferenz Benachbarten Schaufelgitter, *Ing-Arch.* 48 (1979), p. 239.
- (18) Korakianitis, T. P., On the Prediction of Unsteady Forces on Gas Turbine Blades, Part 1 Typical Results & Potential Flow Interaction Effects, ASME Paper 88-GT-89.
- (19) Koya, M. and Kotake, S., Numerical Analysis of Three Dimensional Transonic Periodic Turbine Stages Through Flows, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 51, No. 472 (1985), p. 4239.
- (20) Nishiyama T. and Funazaki, K., Aerodynamic Responses of Turbine Rotor Blade to Sinusoidal Gust of Large Vorticity, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 51, No. 459 (1984), p. 1476. or International Gas Turbine Congress (1983), Paper 3.
- (21) Nishiyama, T. and Funazaki, K., Aerodynamic Responses of Turbine Rotor Blade to Upstream Viscous Wake Rows (Verification of Proposed Method of Analysis by Experiments), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 52, No. 475 (1987).
- (22) Nishiyama, T. and Funazaki, K., Interactions Between the Vorticity of the Incoming Sinusoidal Gust and the Steady Loading of the Rotor Cascade (Vorticity Effects on the Unsteady Characteristics of the Turbine Rotor Cascade), *Trans. Jpn. Soc. Mech. Eng.*, Vol. 55, No. 510 (1989), p. 306.
- (23) Ispas, I., Uber den Einfluss von Nachlaufedellen auf die Stationare Druckverteilung an den Nachfolgenden Schaufelreien In Axial Verdichtern und Axialturbinen, *VDI Berichte* 361 (1980).
- (24) Korakianitis, T. P., On the Prediction of Unsteady Forces on Gas Turbine Blade, Part 2, Viscous Wake Interaction and Axial Gap Effects, ASME Paper 88-GT-90.
- (25) Daiguji, H. and Shirahata, H., A Finite Element Solution of Cascade Flow in a Large Distorted Periodic Flow, *Bull. JSME*, Vol. 21, No. 155 (1978), p. 824.
- (26) Nishiyama, T. and Funazaki, K., Aerodynamic Responses of Compressor and Turbine Cascade to Three Dimensional Sinusoidal Gust, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 52, No. 482 (1986), p. 3435.
- (27) Cumpsty, N. A. and Marble, F. E., The Interaction of Entropy Fluctuations with Turbine Blade Rows-A Mechanism of Turbojet Engine Noise, *Proc. Roy. Soc. A* 357 (1977), p. 323.
- (28) Kramer, P., Computation of Unsteady Blade Forces in Turbomachines by Means of Potential Flow Theory and by Simulating Viscous Wakes, ASME Paper 82-GT-198.
- (29) Radi, M. M., Navier-Stokes Simulations of Rotor-Stator Interactions Using Patched and Overlaid Grids, AIAA Paper 85-1519.
- (30) Shikano, Y., Numerical Analysis of Two Dimensional Unsteady Turbulent Flows in a Turbine Stage, *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 55, No. 515 (1989), p. 1855.
- (31) Rieger, N. F. and Wicks, A. L., Measurement of Nonsteady Forces in Three Turbine Stage Geometries Using the Hydraulic Analogy, *Trans. ASME, J. Eng. Power* 100 (1978), p. 525.
- (32) Heymann, F. J., Turbine Blade Vibration Due to Nozzle Wakes, *Trans. ASME, J. Eng. Power* 91-4 (1969), p. 223.
- (33) Jay, R. L., Structural Response Due to Blade Vane Interaction, *Trans. ASME, J. Eng. Gas Turbine & Power*, 106 (1984), p. 50.
- (34) Shun, Chen, Application of the Rotating Water Table to nozzle wakes excitation in a Low Pressure Turbine, ASME Paper 85-GT-45.
- (35) Nishiyama T. and Funazaki, K., Resonant Oscillation Response of Turbine Rotor Cascade to Viscous Wakes of Upstream Nozzle Cascade (Resonance Amplitude in Bending-Torsion Coupling Oscillation), *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 51, No. 472 (1985), p. 4124.
- (36) Griffin, J. H. and Sinna, A., The Interaction Between Mistuning and Friction in the Forced Response of Bladed Disc Assemblies, *Trans. ASME, J. Eng. Gas Turbine & Power*, 107 (1985), p. 205.

Tetsuo Nishiyama

He was born in January 6, 1924. He has been served as professor of Ishinomaki - Senshu University and emerituss professor of Tohoku University after experiencing professor of Tohoku University and Iwate University. His Research interests are unsteady response of turbine rotor cascade blade, unsteady interaction between stator and rotor, three-dimensional flow around axial flow turbomachinery blade, steady forces of cavitating-hydrofoil in cascade and dynamic behaviour of cavity on hydrofoil.