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Aeroelastic behaviour of the last stage steam turbine blades. Part I. Harmonic oscillations

This paper presents an integrated non-linear numerical model for aeroelasticity predictions of the long steam turbine blade. The approach is based on the solution of the coupled fluid – structure problem in which the aerodynamic and structural dynamic equations are integrated simultaneously in time, thus providing the correct formulation of a problem. The ideal gas flow around multiple interblade passages (with periodicity on the whole annulus) is described by the unsteady 3D Euler equations in conservative form, which are integrated by using the explicit monotonous second – order accurate Godunov-Kolgan, finite volume scheme and moving grids. In the structural analysis the modal approach is used. The natural frequencies and modal shapes of the blade were calculated using 3D finite element model. The instability regions for 5 modes shapes and the distribution of the aerodamping coefficient along the blade length were shown for a harmonic oscillation with the assumed interblade phase angle.

1. Introduction

The aeroelasticity analysis of turbomachinery blades requires the study of a fluid- structure system exposed to unsteady dynamic loading. The nature of the flow in turbomachines is complicated due to the coexistence of subsonic, supersonic and transonic regions. The blade vibration and its interaction with the fluid flow add another dimension to the problem.

A literature survey on flutter prediction methods is beyond the scope of this paper and the interested reader should consult (Marshal and Imregun [1]). However, a brief overview will be given here for the sake of completeness.

Most flutter computations consider a typical sector vibrating in some given assembly mode (or interblade phase angle) for which flutter is expected to occur. In other words, the flutter mode must be known before the analysis, though it is also possible to consider the individual stability of each mode in turn. In such case usually the linear analysis is employed and the interblade phase angle must

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be prescribed at the periodic boundaries.

In recent times the new approaches based on the simultaneous integration in time of the equations of motion for the structure and the fluid have been developed (Bakhle et al. [2], He [3]; Moyround et al. [4], Rządkowski et al. [5], He and Ning [6], Bendiksen [7], Gnesin et el. [8, 9], Carstens and Belz [10], Gnesin et al. [11]). These approaches are very attractive due to the correct formulation of a coupled problem, as the interblade phase angle, at which a stability (instability) would occur, is a part of solution.

In the present study the simultaneous time integration method has been described to calculate the aeroelastic behaviour for a three-dimensional oscillating long steam turbine blade in the transonic gas flow. The individual stability of each mode in turn for a harmonic oscillation with the assumed interblade phase angle is shown.

2. Aerodynamic model

In the present work considered is the 3D transonic flow of an ideal gas through a space multipassage blade row. In general case the flow is assumed to be the aperiodic function from blade to blade (in pitchwise direction), so the calculated domain includes all blades of the whole assembly. The flow equations will be written for a three dimensional Cartesian coordinate system which is fixed to a rotating blade row.

The spatial solution domain is discretized using linear hexahedral elements. The equations of motion are integrated on moving H-H (H-O) – type grid with use of explicit monotonous second-order accuracy Godunov-Kolgan finite-difference scheme (Gnesin and Rządkowski [12]).

We assume that the unsteady fluctuations in the flow are due to prescribed blade motions, and the flows far upstream and far downstream from the blade row are at most small perturbations of uniform free streams. In such case the boundary conditions formulation is based on one – dimensional theory of characteristics, where the number of physical boundary conditions depends on the number of characteristics entering the computational domain.

In general case, when axial velocity is subsonic at the inlet boundary initial values for total pressure, the total temperature and flow angles are used in terms of the rotating frame of reference, while at the outlet boundary only static pressure has to be imposed. Nonreflecting boundary conditions can be used, i.e., incoming waves (three at inlet, one at the outlet) have to be suppressed, which is accomplished by setting their time derivative to zero. On the blade surface, zero flux is applied across the solid surface (the grid moves with the blade).

3. Structural model

The structural model is based on a linear model, the mode shapes and natural frequencies being obtained via standard FE analysis techniques. The mode shapes are interpolated from the structure mesh onto aerodynamic mesh.

The structural part of the aerodynamic equations of motion are uncoupled by using the mode shape matrix and the modal superposition method (see Rządkowski [14] and Gnesin and Rządkowski [12].

Boundary conditions from the structural and aerodynamic domains are exchanged at each step and the aeroelastic mesh is moved to follow the structural motion.

4. Numerical results

Numerical calculations have been carried out for the long steam turbine cascade. The important properties of the blade disc are as given below: the disk inner radius: $r_o = 0.27$ m, the bladed-disk junction radius: $R = 0.667$ m, the blade length: $L = 0.765$ m. All geometrical parameters of the blade are presented in Rzadkowski [14].

Numerical and experimental verification of the numerical code is presented in [15].

Numerical calculations were performed for harmonic oscillations of the blade row according to natural modes with the same amplitude and interblade phase angle (IBPA). The 1^{st} mode mainly performs the bending oscillations, the second one does both bending and torsional oscillations, the third one correspondingly the torsional oscillations, the fourth and fifth modes perform both bending and torsional oscillations. The first five natural mode shapes are shown in Figs. 1-4. The natural frequencies are equal to 41.3 Hz, 99.1 Hz, 216.3 Hz, 220.8 Hz and 320.6 Hz respectively.

The aeroelastic behaviour of vibrating blade row is defined by the aerodamping coefficient D and is equal to the negative work coefficient performed during one cycle of oscillations.

Figs. 6-11 show the aerodamping coefficient (averaged over the blade length) versus the IBPA for the 1^{st}, 2^{nd}, 3^{rd}, 4^{th} and 5^{th} natural mode shapes respectively under harmonic oscillations with different excited frequencies. The negative values of D correspond to the transfer of the mean flow energy to the blade (self-excitation), and positive values to the dissipation of an oscillating blade energy to the flow (aerodamping). The values $f = 25, ..., 400$ Hz correspond to different excitation frequencies.

All curves have typical sinusoidal forms. It can be seen that aerodamping value grows as the oscillation frequency increases.

It should be pointed out that the oscillations according to the first mode (bending oscillations) are characterized by minimal values of aerodamping coefficient near the IBPA of -90 deg (see Fig. 6) and transfer the flow energy to the blade ($D < 0$, flutter condition) for excitation frequencies $f < 50$ Hz. The oscillations according to the third mode (torsional oscillations) have the self-excitation area near the IBPA of 90 deg and for frequencies $f < 300$ Hz (see Fig. 8).

The oscillations according to the 2^{nd} mode in which the both bending and torsional motion occur are damped for all vibration frequencies and have the mi-

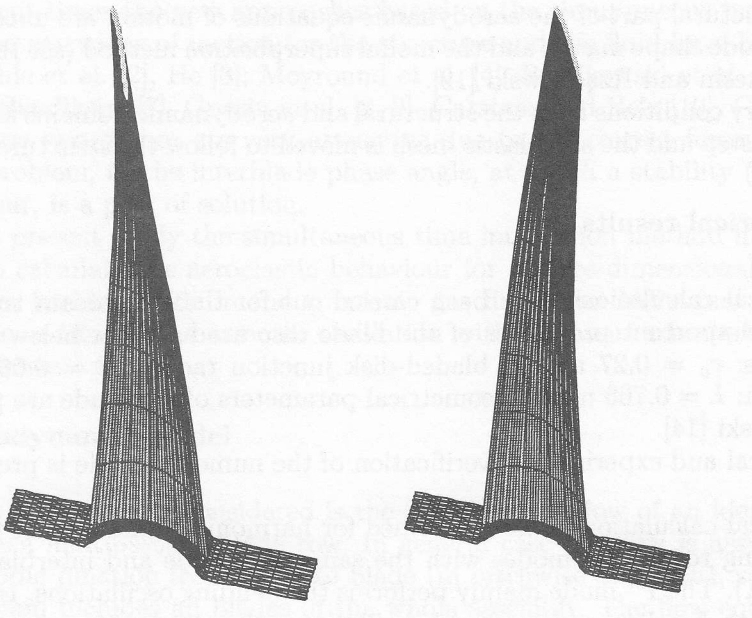

Fig. 1. The 1^{st} mode shape of the last stage steam turbine blade.

Fig. 2. The 2^{nd} mode shape of the last stage steam turbine blade.

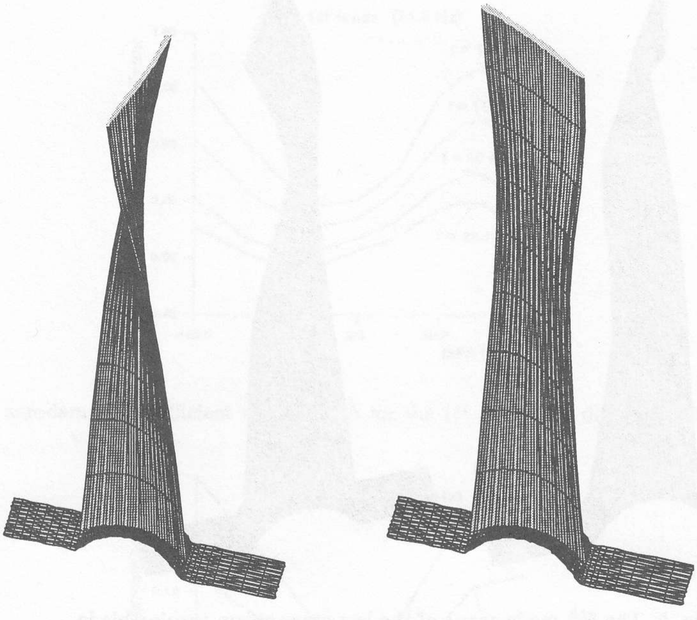

Fig. 3. The 3^{rd} mode shape of the last stage steam turbine blade.

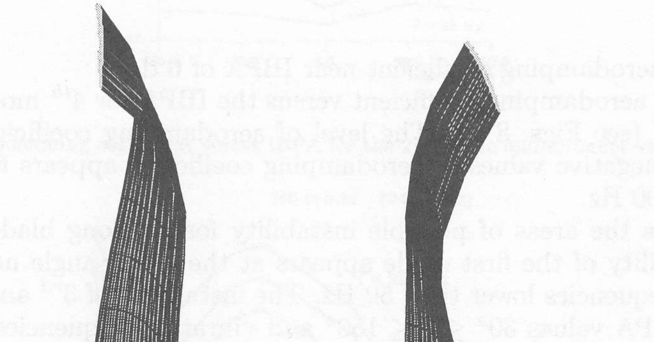

Fig. 4. The 4^{th} mode shape of the last stage steam turbine blade.

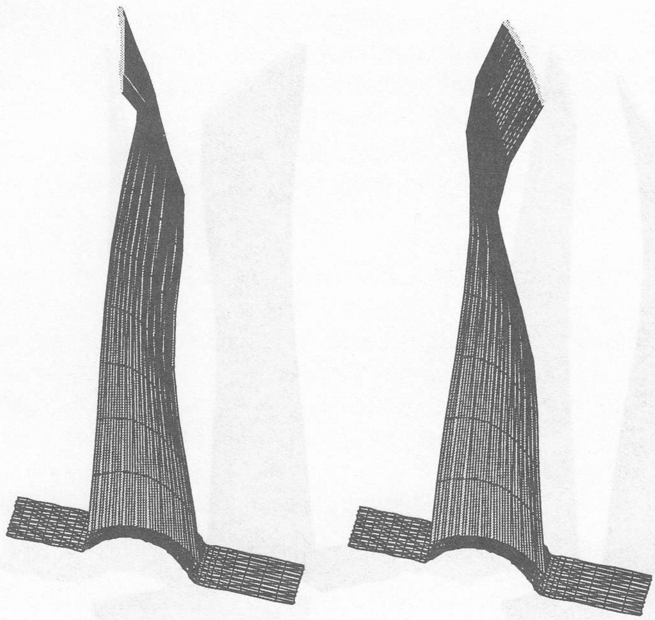

Fig. 5. The 5^{th} mode shape of the last stage steam turbine blade.

nimal values of aerodamping coefficient near IBPA of 0 deg.

The shape of aerodamping coefficient versus the IBPA for 4^{th} mode is similar to the 3^{rd} mode (see Figs. 8, 9). The level of aerodamping coefficient is lower, but the area of negative values of aerodamping coefficient appears for vibration frequency $f < 300$ Hz.

Fig. 11 shows the areas of possible instability for the long blade. It can be seen that instability of the first mode appears at the phase angle near -90 deg and vibration frequencies lower than 50 Hz. The instability of 3^{rd} and 4^{th} modes occurs at the IBPA values $30^o \leq \delta \leq 150^o$ and vibration frequencies lower than 350 Hz. The oscillation according to the 2^{nd} and 5^{th} modes are stable over the full frequency range.

The aerodamping coefficients along the blade length for the wide range of frequencies, for each of five mode shapes in turn and for the IBPA equal to -90 deg and $+90$ deg have been presented in Figs. 12-21.

In these figures the averaged aerodamping coefficient for considered mode shape has been shown as the vertical lines. It is interesting to see that the sign of aerodamping coefficient changes along the blade length. On the some part of the blade it is negative ($D < 0$) (the flutter condition), while on the other part of the blade it is positive ($D > 0$) (the damping condition). These areas are changing for different mode shapes.

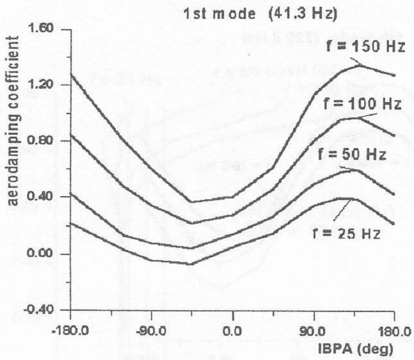

Fig. 6. The aerodamping coefficient versus IBPA for the 1^{st} mode and different vibration frequencies.

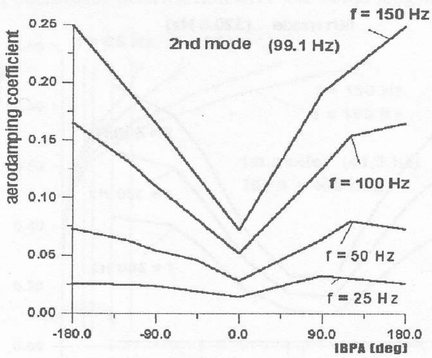

Fig. 7. The aerodamping coefficient versus IBPA for the 2^{nd} mode and different vibration frequencies.

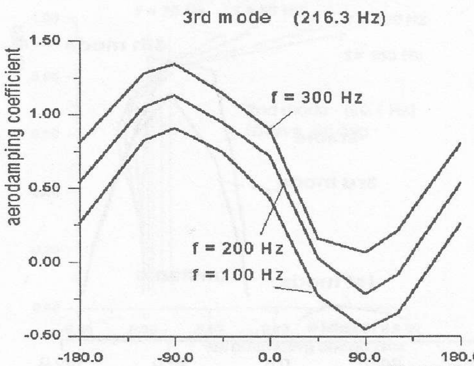

Fig. 8. The aerodamping coefficient versus IBPA for the 3^{rd} mode and different vibration frequencies.

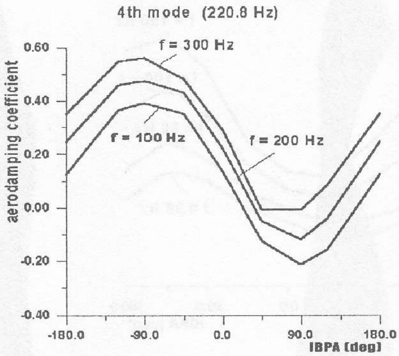

Fig. 9. The aerodamping coefficient versus IBPA for the 4^{th} mode and different vibration frequencies.

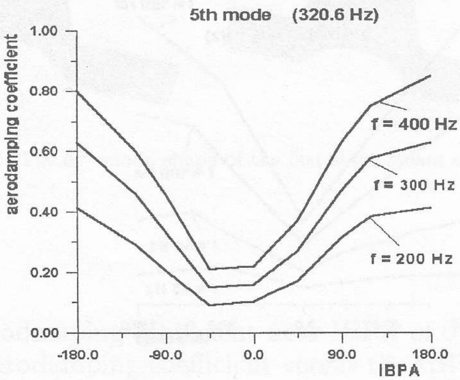

Fig. 10. The aerodamping coefficient versus IBPA for the 5^{th} mode and different vibration frequencies.

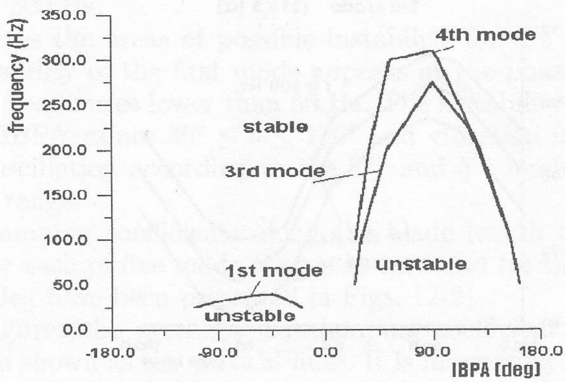

Fig. 11. Stability (instability) areas for the 1^{st} natural modes of oscillations.

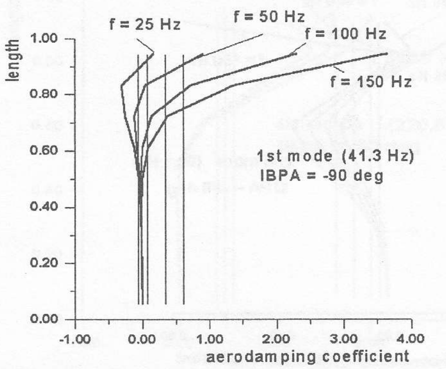

Fig. 12. The aerodamping coefficient distribution over the blade length for the 1^{st} mode, IBPA$= -90$ deg.

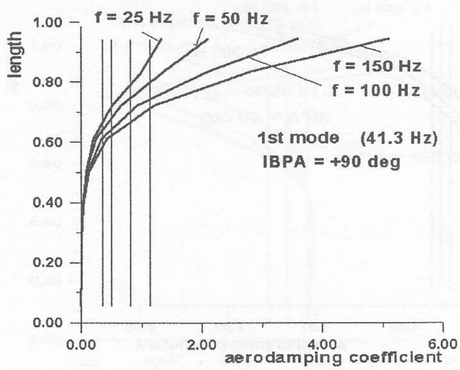

Fig. 13. The aerodamping coefficient distribution over the blade length for the 1^{st} mode, IBPA$=$ 90 deg.

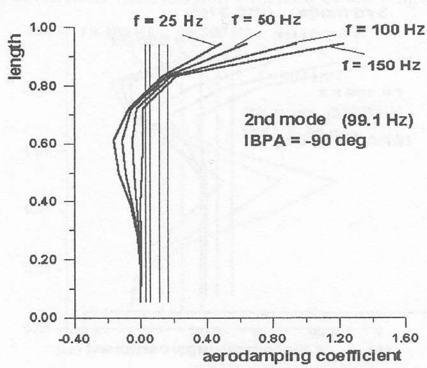

Fig. 14. The aerodamping coefficient distribution over the blade length for the 2^{nd} mode, IBPA$= -90$ deg.

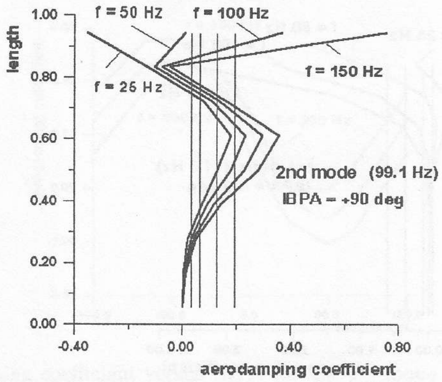

Fig. 15. The aerodamping coefficient distribution over the blade length for the 2^{nd} mode, IBPA= 90 deg.

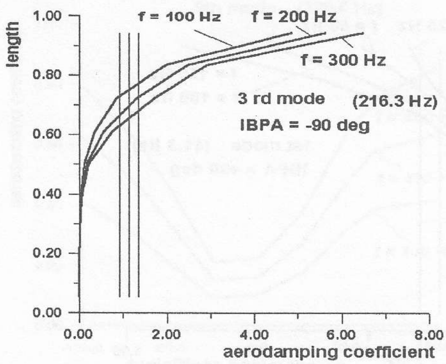

Fig. 16. The aerodamping coefficient distribution over the blade length for the 3^{rd} mode, IBPA= -90 deg.

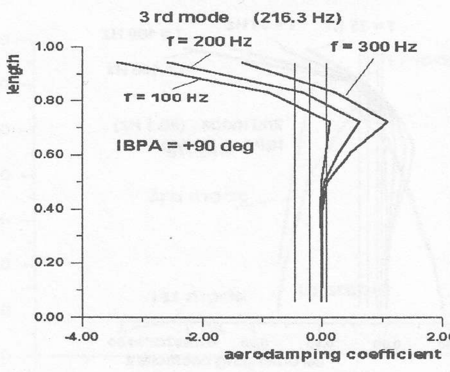

Fig. 17. The aerodamping coefficient distribution over the blade length for the 3^{rd} mode, IBPA= 90 deg.

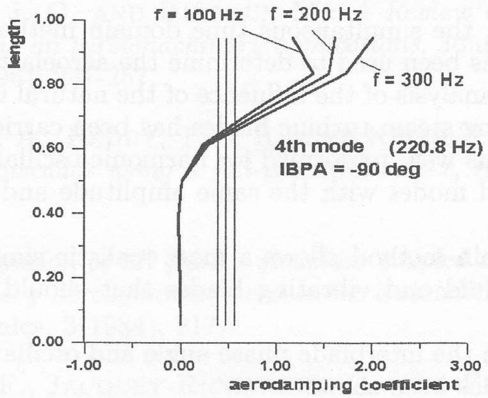

Fig. 18. The aerodamping coefficient distribution over the blade length for the 4^{th} mode, IBPA= −90 deg.

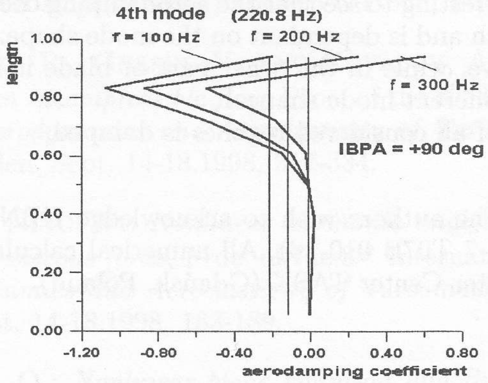

Fig. 19. The aerodamping coefficient distribution over the blade length for the 4^{th} mode, IBPA= 90 deg.

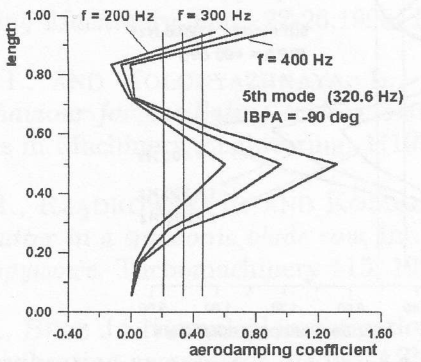

Fig. 20. The aerodamping coefficient distribution over the blade length for the 5^{th} mode, IBPA= −90 deg.

5. Conclusions

In the present study, the simultaneous time domain method and the modal superposition method has been used to determine the aeroelastic stability of the cascade. The numerical analysis of the influence of the natural modes on aeroelastic blade response of long steam turbine blades has been carried out.

Numerical calculations were performed for harmonic oscillations of the blade row according to natural modes with the same amplitude and interblade phase angle (IBPA).

Presented time domain method allows a more realistic simulation of the interaction between the fluid and vibrating blades that should lead to a better physical understanding.

The influence of both the interblade phase angle and oscillation frequency on the aerodamping value has been shown.

The aerodamping coefficient for considered mode shape along the blade length has been shown. It is interesting to see that the aerodamping coefficient sign changes along the blade length and is dependant on the mode shape. In the some part of the blade it is negative, while in the other part of blade it is positive. These areas are changing for different mode shapes.

The blade response of all considered regimes is damped.

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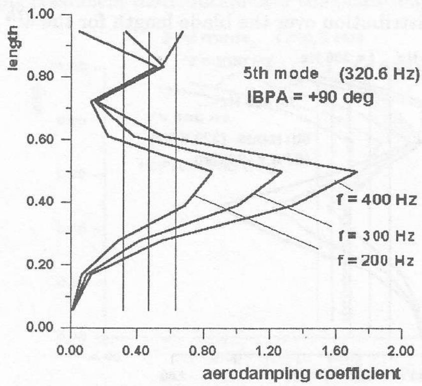

Fig. 21. The aerodamping coefficient distribution over the blade length for the 5^{th} mode, IBPA= 90 deg

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