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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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3D inviscid flutter of IV Standard Configuration. Part I. Harmonic oscillations

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Abstract

A three-dimensional nonlinear time-marching method and numerical analysis for aeroelastic behaviour of oscillating blade row of the IV Standard Configuration has been presented. The approach is based on the solution of the coupled fluid-structure problem in which the aerodynamic and structural equations are integrated simultaneously in time. In this formulation of a coupled problem, the interblade phase angle at which stability (or instability) would occur, is a part of the solution. The ideal gas flow through multiple interblade passage (with periodicity on the whole annulus) is described by the unsteady Euler equations in the form of conservative laws, which are integrated by use of the explicit monotonous second order accurate Godunov-Kolgan finite volume scheme and a moving hybrid H-H (or H-O) grid. The structure analysis uses the modal approach and 3D finite element model of the blade. The blade motion is assumed to be a linear combination of modes shapes with the modal coefficients depending on time. The influence of the natural frequencies on the aerodynamic for the Fourth Standard Configuration is shown. The instability regions for the first two modes shapes and the distribution of the aerodamping coefficient along blade length were shown for a harmonic oscillation with the assumed interblade phase angle.

Keywords: Flutter; Blades; Inviscid flow

1 Introduction

Modern turbomachines operate under very complex regimes where a mixture of subsonic, transonic and supersonic regions coexist. With recent advances in

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the internal compressible flow modelling and increased computational power, it is now possible to undertake both steady and unsteady flow analysis of very complex turbomachinery geometry. The trend for improved gas turbine engine design with higher aerodynamic blade loading and smaller physical size attracts much attention to the aeroelastic behaviour of blades not only in compressors, but also in turbines. Flow-induced blades oscillations of the turbine and compressor can lead to fatigue failures of a construction and so they represent an important problem of reliability, safety and operating cost.

Aeroelasticity phenomena are characterised by the interaction of fluid and structural domains, most prediction methods tend to treat the two domains separately, and they usually assume some critical interblade phase angle for which the flutter analysis is carried out for a single passage.

The undeniable importance of spatial and nonlinear effects for practical turbomachinery configurations has led to the development of three-dimensional methods. Since the early 1980's a number of time accurate Euler and Navier-Stokes procedures have been developed to predict blade row unsteady flows in which unsteadiness is caused by aerodynamic disturbances at the inflow or outflow boundaries, relative motions between the blade rows, or blade vibrations. The traditional approach in flutter calculations of bladed disks is based on frequency domain analysis (Bölcs and Fransson [4], Moyroud, Jacquet-Richardet and Fransson [11]), in which the blade motions are assumed to be harmonic functions of time with a constant phase lag between adjacent blades, and the mode shapes and frequencies are obtained from structural computations. This approach ignores the feedback effect of fluid on the structural vibration.

In recent times, new approaches, based on simultaneous integration in time of the equations of motion for the structure and the fluid, have been developed (Bakhle et al. [1], Bendiksen [2, 3], Carstens and Belz [5], He [6, 7], Kielb [10], Gnesin [9], Gnesin and Rządkowski [8], Rządkowski et al. [13, 14], Vahdati et al. [17]. These approaches are very attractive due to a general 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 blade row of the IV Standard Configuration in the transonic gas flow for a harmonic motion. The influence of natural frequencies on the aerodynamics of considered cascade is shown. The instability regions for the first two mode shapes and the distribution of the aerodamping coefficient along the blade length were shown for a harmonic oscillation with the assumed frequency, mode shape and interblade phase angle.

2 Aerodynamic model

The flow model is described in detail in (Gnesin and Rządkowski [8]), a brief summary will be given here for the sake of completeness. Considered is the 3D transonic flow of an ideal gas through a multipassage blade row. In the general case the flow is assumed to be a periodic function from blade to blade (in pitchwise direction), so the calculated domain includes all blades of the whole assembly (Fig. 1).

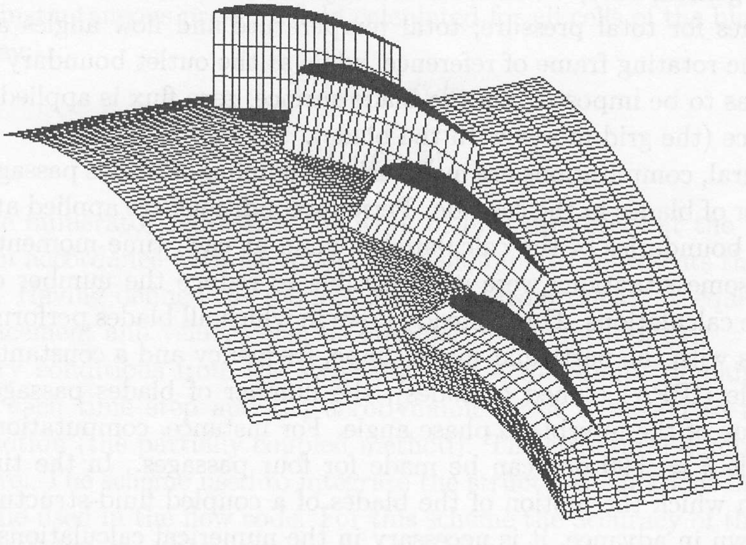

Figure 1. A view of a sector of the whole blade assembly.

The flow equations will be written for a three dimensional Cartesian coordinate system which is fixed to a rotating blade row. In this case, the conservative form of the unsteady Euler equations is given (Gnesin and Rządkowski [8]):

$$\frac{\partial}{\partial t}\int_{\Omega} \vec{f} d\Omega + \oint \vec{F} \cdot \vec{n} d\sigma + \int_{\Omega} \vec{H} d\Omega = 0 \,. \qquad (1)$$

Here $\vec{f}$ is the solution vector, $\vec{F}$ is the inviscid flux through the lateral area σ bounding the finite volume Ω, and $\vec{H}$ is source vector which contains the terms due to the rotation of the coordinate system. The above system of equations is completed by the perfect gas equation

$$p = \rho\varepsilon(\chi - 1) \,, \qquad (2)$$

where χ denotes the ratio of the fluid specific heats ε is an internal energy of mass unit. The spatial solution domain is discretized using linear hexahedral elements.

The equations (1-2) are integrated on moving H-H (or H-O) – type grid with use of explicit monotonous second-order accuracy Godunov-Kolgan difference scheme.

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. So 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 the general case, when axial velocity is subsonic, at the inlet boundary initial values for total pressure, 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. On the blade surface, zero flux is applied across the solid surface (the grid moves with the blade).

In general, computations are made using a number of blades passages equal to the number of blades in the cascade. Periodic conditions are applied at the upper and lower boundaries of the calculated domain at each time moment. However there are some situations were it is possible to reduce the number of passages used in the calculations. For unsteady flows in which all blades perform harmonic oscillations with the particular mode shape, frequency and a constant interblade phase angle (IBPA) (tuned cascades), the number of blades passages depends on the value of the interblade phase angle. For instance, computations with the phase angle $\delta = \pm 90$ deg can be made for four passages. In the time domain method, in which the motion of the blades of a coupled fluid-structure problem is not known in advance, it is necessary in the numerical calculations to include all blade passages. The time step at the coupled calculations is assumed to be constant and is chosen from the stability conditions of the explicit scheme for the fluid model.

3 Structural model

The structural model is based on a linear modal model (Rządkowski [12]), the mode shapes and natural frequencies being obtained via standard FE analysis techniques. Each blade is treated as an individual during the numerical calculations.

The structural part of the aeroelastic equations of motion is uncoupled using the mode shape matrix.

The displacement of each blade can be written as a linear combination of the first N modes shapes with the modal coefficients depending on time:

$$\vec{u}(x,t) = \vec{U}(x,t)\vec{q}(t) = \sum_{i=1}^{N} \vec{U}_i(x)q_i(t), \tag{3}$$

where $\vec{U}(x)$ is the displacement vector corresponding to ith mode shapes, $q_i(t)$ is the modal coefficient of ith mode.

Functions $\vec{U}$ satisfy the orthogonality conditions and normalisation condition, so the equation of motion reduces to the set of independent differential equations relatively to modal coefficients of modes shapes:

$$\ddot{q}_i(t) + \omega_i^2 q_i(t) = \lambda_i(t) . \tag{4}$$

Recalculation of modal forces λ_i is performed on each iteration (see [8], [12]) with use of instantaneous pressure field calculated for all cells of the blade, in the following way:

$$\lambda_i = \frac{\iint\limits_{\sigma} p\vec{U}_i \cdot \vec{n}^o d\sigma}{\iiint\limits_{v} \rho \vec{U}_i^2 dv} . \tag{5}$$

Here the numerator represents the work of pressure forces at the blade displacement in accordance with ith mode, the denominator represents the normalising factor. Having defined the modal coefficients from the set of equations (5), blade displacement and velocity can be obtained in the form of (5).

Boundary conditions from the structural and aerodynamic domains are exchanged at each time step and the aerodynamic mesh is moved to follow the structure motion (the partially coupled method). The structural damping is not included here. The scheme used to integrate the structural equations is the same as the scheme used in the flow code. For this scheme the accuracy of the calculations of natural frequencies and mode shapes is sufficient. The integration scheme introduces damping; this value is very small and was found from calculations done with the aerodynamic forces set to zero.

4 Numerical results

The numerical calculations have been carried out for the turbine cascade known as the Fourth Standard Configuration, which has been experimentally investigated in the nonrotating annular cascade tunnel in transonic flow (Bölcs and Fransson [4]). The numerical and experimental verification of the numerical code presented here can be found in [14].

The influence of the interblade phase angle on the aerodamping coefficient for the assumed bending oscillations (the rigid body motion of the profile, with the free root cross-section) has been shown [14]. From these results the strong influence of IBPA is visible. In the range of -120 deg $<$ IBPA < -30 deg the aerodamping coefficients have negative values, that corresponds to the transfer of energy from the flow to the oscillating blades. The maximum aerodamping coefficient is for IBPA close to 90 deg. In this case the aerodamping coefficient does not depend on the blade length. The experimental values of the aerodamping coefficient is close to the calculated results although the small difference is found in the vicinity of the maximum value of the aerodamping coefficient (see Rządkowski and Gnesin [14]).

In the next step of the numerical study the influence of the first four mode shapes on the blade response in the harmonic motion is shown, where the blades vibrate with the assumed frequency, mode shape and the interblade phase angles. The mode shapes of the considered blade are presented in Fig 2. The first mode is mainly the bending mode, the second one is the torsional mode, the third and fourth ones are the bending-torsion modes. The natural frequencies are equal to the 150 Hz, 750 Hz, 900 Hz and 1050 Hz respectively.

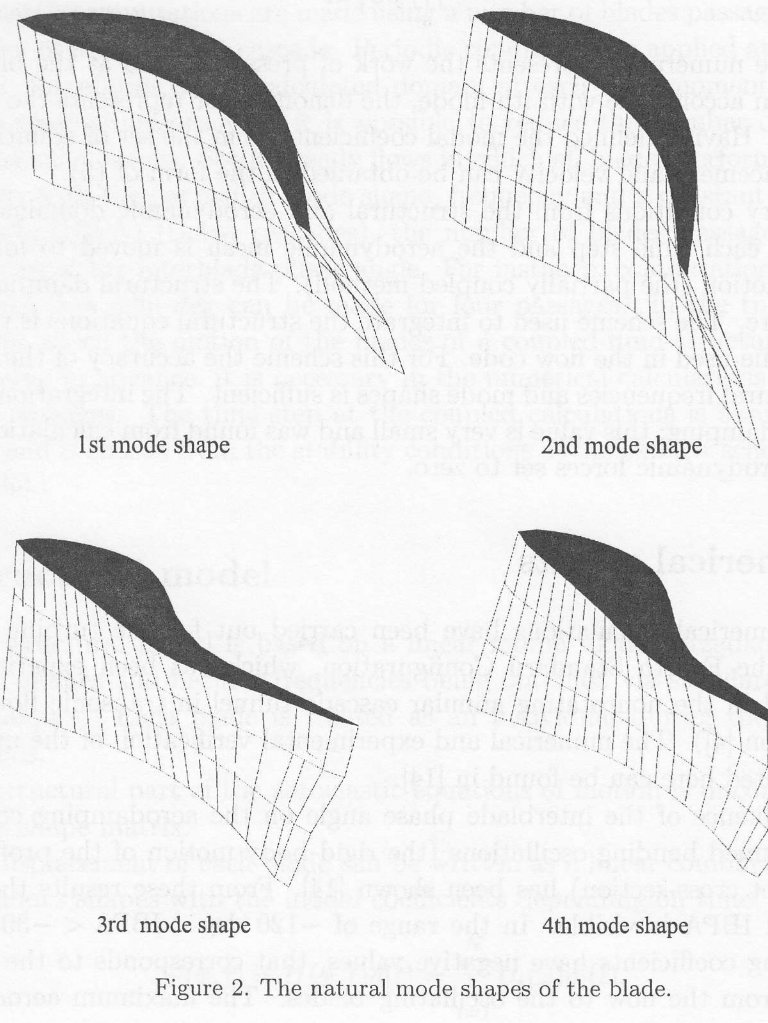

Figure 2. The natural mode shapes of the blade.

In our calculation the blade will vibrate with the natural frequencies (150 Hz, 750 Hz, 900 Hz and 1050 Hz respectively) and with the mode shape corresponding to these natural frequencies.

Figures 3 and 4 show the aerodamping coefficient versus the interblade phase angle for the first and second natural mode shapes of STC4 respectively under harmonic oscillations with different excitation frequencies f. The negative values of the aerodynamic coefficient corresponds to the transfer of energy from the flow to the blade (self-excitation), and the positive values – to dissipation of an oscillating blade energy to the flow. All curves have the typical sinusoidal forms. It is seen that the aerodamping grows as the oscillation frequency increases.

It should be pointed out that the oscillations according to the first mode (bending oscillations) are characterised by the negative values of aerodamping coefficient near the IBPA of -90 deg and $f < 150$ Hz (see Fig. 3), while the oscillations according to the second mode have the self-excitation area near the IBPA of 90 deg and $f < 250$ Hz (see Fig. 4).

The influence of the phase angle on the sign of the aerodamping coefficient is important for the low modes of vibration and low natural frequencies. It decreases with increasing of the mode number and natural frequency f. The aerodamping coefficient grows almost linearly taking positive values over all frequency range except the area of low frequencies ($f < 300$ Hz). Figure 5 shows the areas of possible instability for STC4 (IV Standard Configuration). It can be seen that instability of the first mode appears at the phase angle equal to -90 deg ($f < 150$ Hz) whereas the instability of the second mode appears at phase angle equal to $+90$ deg ($f < 250$ Hz). The higher the natural modes the more stable the cascade is, over the full frequency range.

Calculation of the aerodamping coefficient for the cascade vibrating according to the third and fourth modes show that the cascade is stable for all interblade phase angles. The influence of the phase angle on the aerodamping coefficient is important for the low modes of vibration and low natural frequencies. It decreases with increasing of the mode number and natural frequencies.

The effect of three-dimensionality (the results for the three cross-sectional areas) on aerodamping coefficient for the wide range of frequencies under the IBPA values of -90 deg and $+90$ deg is given in Figs. 6-14.

Here the numbers 1, 2 and 3 correspond to the root, mid and tip sections of the blade and letter s corresponds to the averaged along blade length aerodamping coefficient value. As it has seen from figures the tip section of the blade is characterized by highest values of damping (or self-excitation) then the hub section.

It is interesting to see that the aerodamping coefficient sign changes along the blade length close to the frequency 150 Hz , for 1st bending mode and the

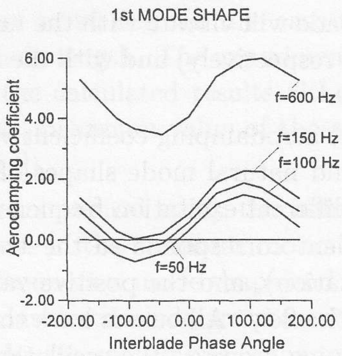

Figure 3. Aerodamping coefficient versus interblade phase angle for the 1st mode of vibration and different vibration frequencies.

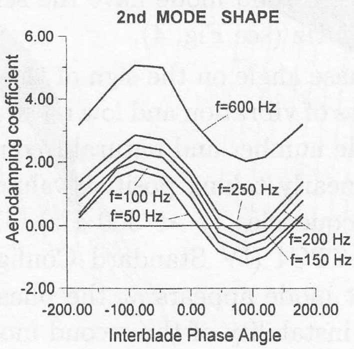

Figure 4. Aerodamping coefficient versus interblade phase angle for the 2nd mode of vibration and different vibration frequencies.

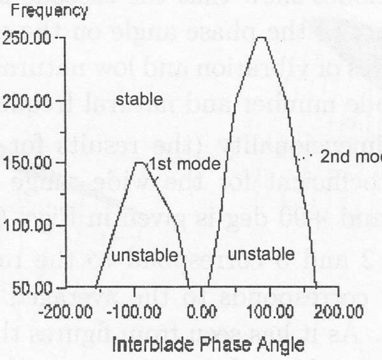

Figure 5. The stability regions for the 1st and 2nd mode shapes.

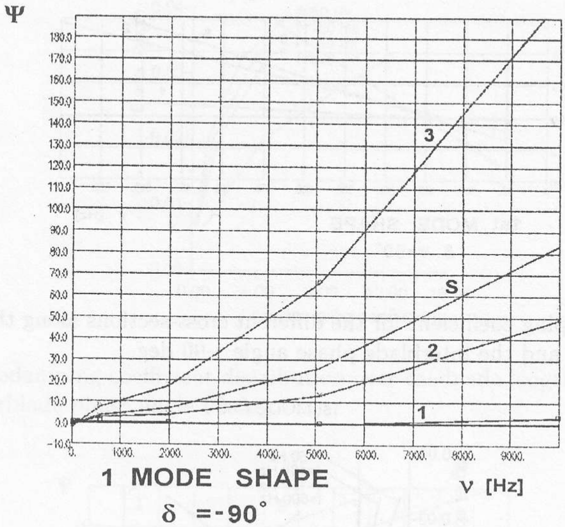

Figure 6. The aerodamping coefficient for the different cross-sections along the blade length, for the 1st mode shape and the interblade phase angle −90 deg.

interblade phase angle −90 deg (see Fig. 8). On some part of the blade is negative (the flutter condition), while on the other part of the blade is positive (the damping condition). These areas are changing for different natural frequencies, mode shapes and interblade phase angles (see Figs. 10, 12, 14). For frequencies $f = 50$ Hz, 100 Hz and for the interblade phase angle equal to −90 deg all blade is in the flutter condition. These values are important form the design point of view. The flutter condition in the tip blade region can cause damage. More results of distributions of aerodamping coefficient are presented in Rządkowski and Gnesin [15].

Figures 9, 10 present the aerodynamic coefficient of the 1st mode shape for the interblade phase angle 90 deg. Values of this coefficient along the blade length are positive (the damping condition). Figures 11, 14 present the aerodamping coefficient for the 2nd mode shape and for different phase angles. The aerodamping coefficient for the 2nd mode shape and the interblade phase angle −90 deg is positive, the damping condition (see Figs. 11, 12). The aerodamping coefficient for the 2nd mode shape and the interblade phase angle −90 deg and $f < 150$ Hz is negative (the flutter condition).

The presented time domain method allows a more realistic simulation of the motion of fluid and the cascade blades that should lead to a better physical understanding.

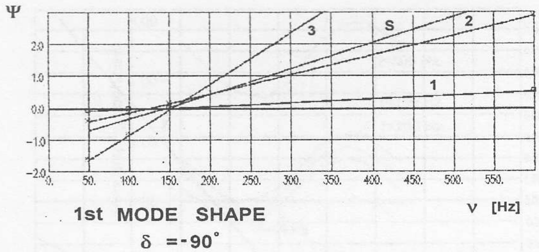

Figure 7. The aerodamping coefficient for the different cross-sections along the blade length, for the 1st mode and the interblade phase angle −90 deg.

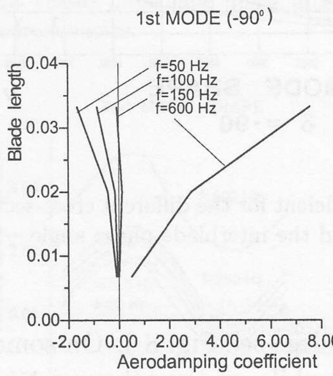

Figure 8. The aerodamping coefficient distribution over the blade length, for the 1st mode and the interblade phase angle 90 deg.

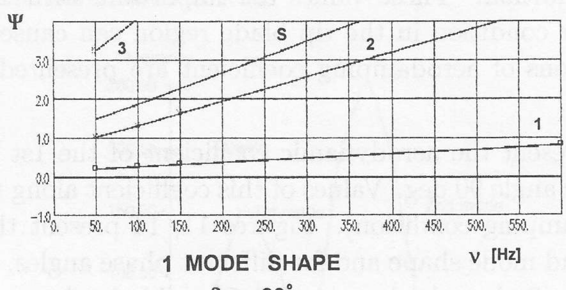

Figure 9. The aerodamping coefficient for the different cross-sections along the blade length, for the 1st mode and the interblade phase angle 90 deg.

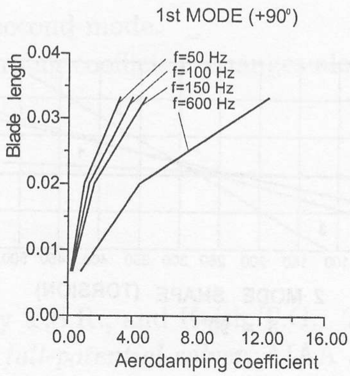

Figure 10. The aerodamping coefficient distribution over the blade length, for the 1st mode and the interblade phase angle 90 deg.

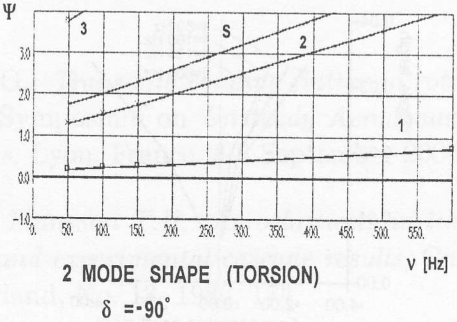

Figure 11. The aerodamping coefficient for the different cross-sections along the blade length, for the 2nd mode and the interblade phase angle −90 deg.

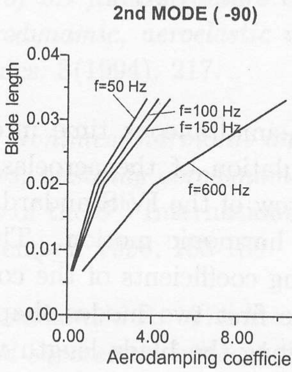

Figure 12. The aerodamping coefficient distribution over the blade length, for the 2nd mode and the interblade phase angle −90 deg.

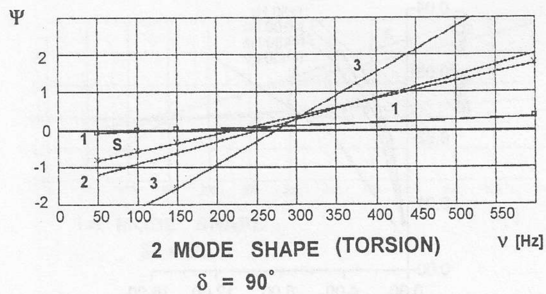

Figure 13. The aerodamping coefficient for the different cross-sections along the blade length, for the 2nd mode and the interblade phase angle 90 deg.

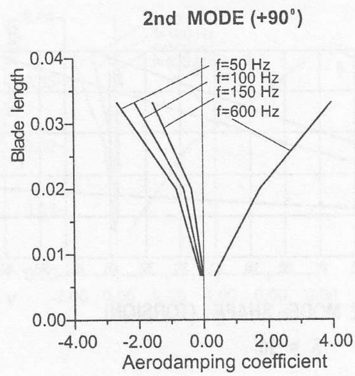

Figure 14. The aerodamping coefficient distribution over the blade length, for the 2nd mode and the interblade phase angle −90 deg.

5 Conclusions

In the present study the simultaneous time integration method has been described which enables calculation of the aeroelastic behaviour for a three-dimensional oscillating blade row of the IV Standard Configuration in the transonic gas flow in the case of harmonic motion. The influence of the natural frequencies on the aerodamping coefficients of the considered cascade is shown. The instability regions for the first two modes shapes and the distribution of the aerodamping coefficient along the blade length were shown for a harmonic oscillation with the assumed frequency, mode shape and interblade phase angle.

It was found that torsion a 2nd mode of vibration is less stable than the 1st bending one. The aerodamping coefficient is negative (the flutter condition) in the area close to the interblade phase angle equal to −90 deg for the 1st mode and to +90 deg for the second mode.

Value of the aerodamping coefficient changes along the blade length.

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