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DEVELOPMENT OF AN AEROELASTIC ANALYSIS INCLUDING A VISCOUS FLOW MODEL

by

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Under this grant, Version 4 of the three-dimensional Navier-Stokes aeroelastic code (TURBO-AE) has been developed and verified. The TURBO-AE Version 4 aeroelastic code allows flutter calculations for a fan, compressor, or turbine blade row. This code models a vibrating three-dimensional bladed disk configuration and the associated unsteady flow (including shocks, and viscous effects) to calculate the aeroelastic instability using a work-per-cycle approach. Phase-lagged (time-shift) periodic boundary conditions are used to model the phase lag between adjacent vibrating blades. The direct-store approach is used for this purpose to reduce the computational domain to a single interblade passage. A disk storage option, implemented using direct access files, is available to reduce the large memory requirements of the direct-store approach. Other researchers have implemented 3D inlet/exit boundary conditions based on eigen-analysis.

The TURBO-AE Version 4 code has been verified and the results reported in Ref. 1 (included here as Appendix A). In Ref. 1, unsteady pressure, lift, and moment distributions are presented for a helical fan test configuration that is used to verify the code by comparison to two-dimensional linear potential (flat plate) theory. The results are for pitching and plunging motions over a range of phase angles. Good agreement with linear theory is seen for all phase angles except those near acoustic resonances. The agreement is better for pitching motions than for plunging motions. The reason for this difference is not understood at present. Numerical checks have been performed to ensure that solutions are independent of time step, converged to periodicity, and linearly dependent on amplitude of blade motion.

The TURBO-AE Version 4 code is based on the TURBO code Version 1.2. During the grant period, NASA made a new base TURBO code available. The new features in TURBO Version 3.1 included improved convergence through rotating frame calculations, improved steady and unsteady viscous flow modeling with algebraic or k-epsilon turbulence models, improved capability of using start-up solutions from other steady codes such as APNASA, real gas modeling, namelist input capability, and cross-platform portability and improved memory management with Fortran 90 code. In order for the aeroelastic calculations to benefit from these new features, it was necessary to transfer all the relevant aeroelastic coding from TURBO-AE Version 4 to the new TURBO code.

An aeroelastic pre-processor code (named AE-prep) was developed which contains the modeshape interpolation and grid deformation parts of the TURBO-AE Version 4 code. This pre-processor works with the latest versions of the TURBO code (Version 3.1 and Version 4.1) to restore the aeroelastic analysis capability that was present in TURBO-AE Version 4. In addition, the pre-processor allows the use of the most recent versions of the TURBO code for aeroelastic analysis without the long delays associated with the merging of AE modifications into each new version of TURBO – as was necessary with the TURBO-AE code. Thus, the aeroelastic analysis can benefit from all the new and improved features present in the latest versions of the TURBO code. The TURBO Version 3.1 code was exercised for blade vibration calculations and support was provided to NASA and its industry customers using TURBO code for their aeroelastic applications.

Appendix B includes a report that presents representative unsteady aerodynamic results for blade vibration from the Euler / Navier-Stokes unsteady aerodynamic code TURBO Version 3.1. Unsteady pressure, lift, and moment distributions are presented for a helical fan test configuration that is used to verify the code by comparison to two-dimensional linear potential (flat plate) theory. The results are for pitching and plunging motions over a range of phase angles. Good agreement with linear theory is seen for all phase angles except those near acoustic resonances. The agreement is better for sub-resonant conditions than for super-resonant conditions. Note that TURBO Version 3.1 does not have the 3D inlet/exit boundary based on eigen-analysis that were implemented in TURBO-AE Version 4. Hence some differences are expected between the results of Appendix A and Appendix B.

Reference

[1] Bakhle, M. A., Srivastava, R., Keith, T. G. Jr., and Stefko, G. L., "Aeroelastic Calculations Based Three-Dimensional Euler Analysis", AIAA Paper 98-3295, July 1998.

Appendix A

AEROELASTIC CALCULATIONS BASED ON THREE-DIMENSIONAL EULER ANALYSIS

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Abstract

This paper presents representative results from an aeroelastic code (TURBO-AE) based on an Euler / Navier-Stokes unsteady aerodynamic code (TURBO). Unsteady pressure, lift, and moment distributions are presented for a helical fan test configuration which is used to verify the code by comparison to two-dimensional linear potential (flat plate) theory. The results are for pitching and plunging motions over a range of phase angles. Good agreement with linear theory is seen for all phase angles except those near acoustic resonances. The agreement is better for pitching motions than for plunging motions. The reason for this difference is not understood at present. Numerical checks have been performed to ensure that solutions are independent of time step, converged to periodicity, and linearly dependent on amplitude of blade motion. The paper concludes with an evaluation of the current state of development of the TURBO-AE code and presents some plans for further development and validation of the TURBO-AE code.

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Introduction

There is an ongoing effort to develop technologies to increase the fuel efficiency of commercial aircraft engines, improve the safety of engine operation, reduce the emissions, and reduce engine noise. With the development of new designs of ducted fans, compressors, and turbines to achieve these goals, a basic aeroelastic requirement is that there should be no flutter or high resonant blade stresses in the operating regime. In order to verify the aeroelastic soundness of the design, an accurate prediction of the unsteady aerodynamics and structural dynamics of the propulsion component is required. The complex geometry, the presence of shock waves and flow separation makes the modeling of the unsteady aerodynamics a difficult task. The advanced blade geometry, new blade materials and new blade attachment concepts make the modeling of the structural dynamics a difficult problem.

Computational aeroelastic modeling of fans, compressors, and turbines requires many simplifying assumptions. For instance, flutter calculations are typically carried out assuming that the blade row is isolated. This simplifies the structural dynamics formulation and the unsteady aerodynamic calculations considerably.

For an isolated blade row flutter calculation, the modeling of the unsteady aerodynamics is the biggest challenge. Many simplifying assumptions are made in the modeling of the unsteady aerodynamics. In the past, panel methods based on linear compressible small-disturbance potential theory have been used to model the unsteady aerodynamics and aeroelasticity of fans in subsonic flow; see for example [1,2]. The major limitations of this type of analysis are the neglect of transonic, vortical, and viscous flow effects in the model. These inherent limitations in the model preclude its use in a majority of practical applications. A full potential unsteady aerodynamic analysis has been used with a modal structural dynamics method to model the aeroelastic behavior of fan blades [3,4]. Although the full potential aerodynamic formulation is able to model transonic effects (limited to weak shocks), the vortical and viscous effects are still neglected. For example, the blade tip vortex, or a leading-edge vortex is not modeled. Recently, researchers [5-10] have also developed inviscid and viscous unsteady aerodynamic analyses for vibrating blades.

For aeroelastic problems in which viscous effects play an important role (such as flutter with flow separation, or stall flutter, and flutter in the presence of shock and boundary-layer interaction), a more advanced aeroelastic computational capability is required. The authors of this paper have earlier presented [11] some results from the TURBO-AE aeroelastic code. Initial calculations were restricted to in-phase (zero phase angle) blade motions and inviscid flow. In a later paper [12], results were presented for zero and non-zero phase angle motions and viscous flow. In these calculations, multiple blade passages were modeled for non-zero phase angle motions. Most recently [13], results have been presented using a single blade passage with phase-lag periodic boundary conditions to model arbitrary phase angle motions.

This paper presents unsteady pressure, lift, and moment distributions due to blade vibration over a range of phase angles for verification of the TURBO-AE aeroelastic code. For non-zero phase angle motions, phase-lag periodic boundary conditions are used. The configuration selected is a helical fan. The geometry and flow conditions are chosen to minimize non-linear and three-dimensional effects since the intent is to verify the code by comparison with two-dimensional linear potential (flat plate) theory.

Aeroelastic Code – TURBO-AE

This section briefly describes the aeroelastic code (TURBO-AE); previous publications [11-13] provide additional details. The TURBO-AE code is based on an unsteady aerodynamic Euler / Navier-Stokes code (TURBO), developed separately [14,15]. The TURBO code provides all the unsteady aerodynamics to the TURBO-AE code.

The TURBO code was originally developed [14] as an inviscid flow solver for modeling the flow through turbomachinery blade rows. Additional developments were made [15] to incorporate viscous effects into the model. This Reynolds-averaged Navier Stokes unsteady aerodynamic code is based on a finite volume scheme. Flux vector splitting is used to evaluate the flux Jacobians on the left hand side of the governing equations [14] and Roe's flux difference splitting is used to form a higher-order TVD (Total Variation Diminishing) scheme to evaluate the fluxes on the right hand side. Newton sub-iterations are used at each time step to maintain higher accuracy. Symmetric Gauss-Seidel iterations are applied to the discretized equations. A Baldwin-Lomax algebraic turbulence model is used in the code.

The TURBO-AE code assumes a normal mode representation of the structural dynamics of the blade. A work-per-cycle method is used to determine aeroelastic stability (flutter). Using this method, the motion of the blade is prescribed to be a harmonic vibration in a specified in-vacuum normal mode with a specified frequency (typically the natural frequency). The work done on the vibrating blade by aerodynamic forces during a cycle of vibration is calculated. If work is being done *on* the blade by the aerodynamic forces at the end of a vibration cycle, the blade is dynamically unstable, since it will result in extraction of energy from the flow, leading to an increase in amplitude of oscillation of the blade.

The inlet/exit boundary conditions used in this code are described in [16-18]. For cases in which the blade motions are not in-phase, phase-lag periodic boundary conditions based on the direct store method are used.

Results

In this section, results are presented which serve to verify the TURBO-AE code. The test configuration selected is a helical fan [16]. This configuration consists of a rotor with twisted flat plate blades enclosed in a cylindrical duct with no tip gap. This configuration was developed by researchers [16] to provide a relatively simple test case for comparison with two-dimensional analyses. The geometry is such that three-dimensionality of the flow is minimized.

The parameters of this three-dimensional configuration are such that the mid-span location corresponds to a flat plate cascade with a stagger angle of 45 deg. and unit gap-to-chord ratio operating in a uniform mean flow at a Mach number of 0.7 parallel to the blades. The rotor has 24 blades with a hub/tip ratio of 0.8. The inlet flow (axial) Mach number used in this calculation is 0.495, which results in a relative Mach number of approximately 0.7 at the mid-span section. The results presented are for inviscid runs of the TURBO-AE code.

The grid used for the calculations is 141×11×41 in one blade passage. On each blade surface, 81 points are located in the chordwise direction and 11 points in the spanwise direction. The inlet and exit boundaries are located at an axial distance of approximately 0.7 chord lengths from the blade leading and trailing edges. To begin, a steady solution is obtained for this configuration. The steady flowfield consists of uniform flow at each radial location.

Aeroelastic calculations are performed starting from the steady solution. Calculations have been performed for harmonic blade vibration in plunging and pitching modes, separately. The pitching is about the mid-chord. The prescribed mode shapes are such that the amplitude of vibration does not vary along the span. This choice of mode shapes is meant to reduces the three-dimensionality of the unsteady flowfield for ease of comparison with two-dimensional analyses.

The vibration frequency is selected so that the non-dimensional reduced frequency based on blade chord is 1.0 at the mid-span. A study was performed to determine the sensitivity of numerical results to the number of time steps used in each cycle of blade vibration. Calculations were done with 100, 200, and 300 time steps per cycle of vibration for 0 deg. phase angle plunging motion. The time step was varied so as to keep the vibration time period (or frequency) fixed. Figure 1 shows the work-per-cycle from this study. As the flowfield reaches periodicity, it can be seen that the results are nearly identical for 200 and 300 time steps per cycle. These results differ slightly from the results for 100 time steps per cycle. Figure 2 shows the unsteady pressure difference for the same three numbers of time steps per cycle. The results for 200 and 300 time steps per cycle are indistinguishable. Based on such calculations, it was determined that 200 time steps per cycle provided adequate temporal resolution for the selected vibration frequency. All results presented here have been obtained using 200 time steps per cycle.

The non-dimensional time step used in the calculations (with 200 time steps per cycle) is 0.045, which results in a maximum CFL number of 60.5. The amplitude of blade vibrations in the calculation is a pitching amplitude of 0.2 deg. or a plunging amplitude of 0.1% chord. In all cases, calculations were continued for a number of cycles of blade vibration to allow the flowfield to become periodic. Initial calculations with phase angles of 0, 45, 90, 135, 180, 225, 270, and 315 deg. were continued for 15 cycles of blade vibration to ensure periodicity. Later calculations with intermediate phase angles (22.5, 67.5, ... , and 337.5 deg.) were continued only for 10 cycles of blade vibration due to insufficient computational resources. In an earlier study [13], it was shown that, for the various phase angles studied, the flowfield became periodic after about 7-10 cycles of blade vibration. Hence, the 10 or 15 cycles used in the present work were considered adequate to reach periodicity.

Figure 3 shows the unsteady moment about mid-chord (in complex form) for pitching blade motion about the mid-chord. These results are from the mid-span location and were calculated using the first harmonic of the unsteady blade surface pressure difference. Semi-analytical results from two-dimensional linear potential (flat plate) theory [19] are included for comparison.

The overall level of agreement between TURBO-AE results and linear theory is very good, with exceptions to be discussed in the following paragraph. For subsonic flows and small amplitude of blade motions, it is expected that there will be no significant difference between the Euler and linear potential results. Hence, the observed agreement is not surprising and provides a basic verification of the TURBO-AE code. It may be noted that the parameters of the present configuration were selected [16] to allow exactly this type of a verification by comparison to two-dimensional analyses.

In Figure 3, some deviation from linear theory is seen in the results for phase angles of 112.5 and 135 deg., and to a lesser extent for phase angles of 157.5 and 315 deg. All these phase angles fall near conditions of acoustic resonance (or cut-off conditions) in the corresponding two-dimensional flat plate cascade. The acoustic resonances occur at phase angles of 107.3 and 330.6 deg.; these values are marked on the phase angle axis of Figure 3 for reference. The phase angles between these resonances are associated with sub-resonant [20] (cut-off) conditions in which all disturbances attenuate away from the cascade. No disturbances propagate in the upstream or downstream directions under sub-resonant conditions. The phase angles between 0 and 107.3 deg. and between 330.6 and 360 deg. are associated with super-resonant (cut-on) conditions in which at least one disturbance propagates in either the far upstream or downstream direction.

The significance of the sub-resonant and super-resonant conditions to computational aeroelasticity can be explained as follows. Since the typical computational domain does not extend very far from the blade row or cascade, the inlet/exit boundary conditions must minimize (or eliminate) the reflection of disturbances generated by the vibration of the blades. For sub-resonant conditions, it may be possible to reduce the reflected disturbances by moving the boundary farther away from the blade row. This is not possible for super-resonant conditions. From Figure 3, it can be seen that the results from TURBO-AE agree well with linear theory for both sub-resonant and super-resonant conditions. It may be also recalled that the computational inlet/exit boundaries are located quite near (0.7 axial chord lengths from leading/trailing edges) the blade row in the present calculations.

Figure 4 shows the unsteady lift (in complex form) for plunging blade motion. As noted for the pitching results, these results are also from the mid-span location and were also calculated using the first harmonic of the unsteady blade surface pressure difference. Results from linear potential theory are included in Figure 4 for comparison. The overall level of agreement with linear theory is good, but not as good as that for pitching motion (Figure 3). The source of such a difference between the plunging and pitching results is not understood. However, such differences in agreement have been noted by other researchers [16,17] for a different configuration. In addition, deviations are observed close to the acoustic resonances, as for pitching.

Figure 5 shows the unsteady blade surface pressure difference (first harmonic) at the mid-span location for pitching blade motion about the mid-chord. Results are presented for phase angles values between 0 and 360 deg. in steps of 22.5 deg. In each case, the linear theory results are included for comparison. In most cases, the agreement with linear theory is very good. The exceptions occur at phase angles near acoustic resonance conditions, as noted earlier in the description of the unsteady moment (Figure 3). It is worth noting that, in this case, the integrated results in Figure 3 accurately represent the level of agreement with linear theory, without obscuring any differences in the details of the pressure distributions.

Figure 6 shows the unsteady blade surface pressure difference (in complex form) for plunging blade motion. The level of agreement with linear theory is not as good as for pitching, as reflected in the unsteady lift (Figure 4). The most serious deviations from linear theory are restricted to the phase angles near conditions of acoustic resonance.

Some of the results for plunging motion (Figure 6) show an irregular (unsmooth) variation in the unsteady pressure distribution which is not seen in any of the results for pitching motion (Figure 5). This uneven variation can be seen in the plunging results in Figures 6b, 6d, 6f, 6h, 6j, 6l, 6n, and 6p for phase angles of 22.5, 67.5, 112.5, ... , and 337.5 deg. One common characteristic of these results is that these were all generated on a workstation and may therefore suffer from some precision-related numerical problem. However, it is surprising to note that the corresponding results for pitching motion (also computed on a workstation) are quite smooth and do not show such unevenness. A re-calculation of selected plunging results on a super-computer does indeed eliminate the unevenness in pressure variation, but the pressure distributions remain substantially unchanged from those presented in Figure 6.

Note that all the TURBO-AE results presented are the first harmonic components of the unsteady variations. The higher harmonics are extremely small for these calculations, indicating the linearity of the unsteady flow. Previous results [12] had shown a nonlinear dependence on amplitude for certain cases for pitching amplitudes of blade vibration of 2 deg., but not at the 0.2 deg. amplitude used in the present calculations.

To investigate the effect of some numerical parameters on the results for phase angle of 112.5 deg. (where the maximum deviation from linear theory is observed), the following calculations were done. The number of time steps per cycle was doubled from 200 to 400, with a corresponding halving of the time step. The unsteady pressure results showed no changes within plotting accuracy, indicating adequate temporal resolution. Similarly, the number of cycles of oscillation was doubled from 10 to 20 to examine possible lack of periodicity. No change in the unsteady pressure results was observed within plotting accuracy. The deviations in the regions of acoustic resonances may possibly be reduced by the use of finer grids. But, such a grid refinement study has not yet been performed.

Concluding Remarks

An aeroelastic analysis code named TURBO-AE has been developed and is being verified and validated. The starting point for the development was an Euler / Navier-Stokes unsteady aerodynamic code named TURBO. Some verification has been done by running the code for a helical fan test configuration. Results have been presented for pitching and plunging blade motions over a range of phase angles. The results compare well with results from a linear potential analysis. This agreement is expected for subsonic flows for which the calculations were made and for the relatively small amplitudes of blade motion.

The agreement is not as good for plunging motion as for pitching motion. The reason for this difference is not understood at present. Also, deviations are observed for values of phase angles near acoustic resonance conditions. The solutions are shown to be independent of the time step, converged to periodicity, and linearly dependent on amplitude of blade motion. This test case provides a basic verification of the TURBO-AE code. It also shows the need to perform a grid refinement study as a possible way to resolve the deviations from linear theory near acoustic resonance conditions and for plunging motion. For plunging motion, some results are affected by precision-related numerical problems, as seen from uneven pressure distributions. But, the elimination of these precision problems does not change the pressure distributions substantially, apart from making the variations smooth.

It is necessary to further verify the TURBO-AE using different standard test configurations to compare with experimental data and other code predictions. This is being done in collaboration with other researchers. Also, it is necessary that the TURBO-AE code be exercised to evaluate its ability to analyze and predict flutter for conditions in which viscous effects are significant. This work is also currently in progress.

Acknowledgments

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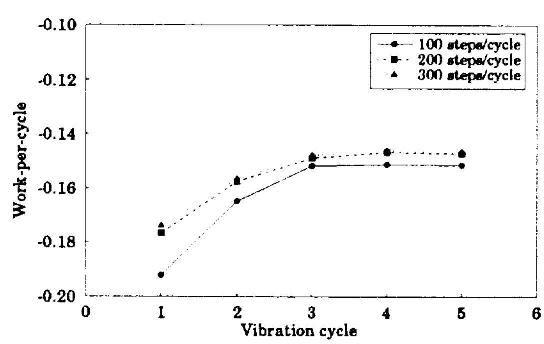


Figure 1: Effect of time steps per cycle on work.

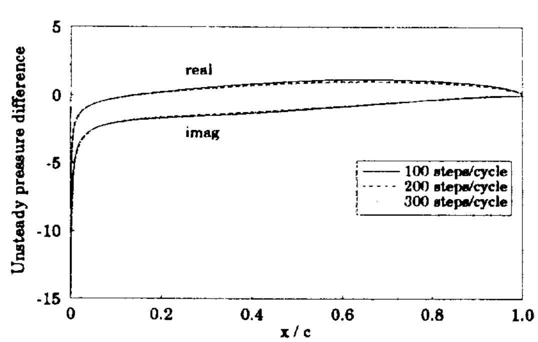


Figure 2: Effect of time steps per cycle on pressure.

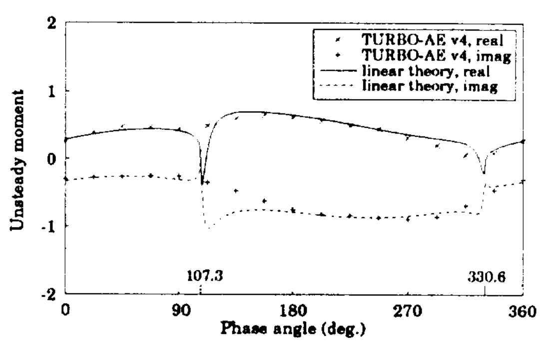


Figure 3: Unsteady moment for pitching motion.

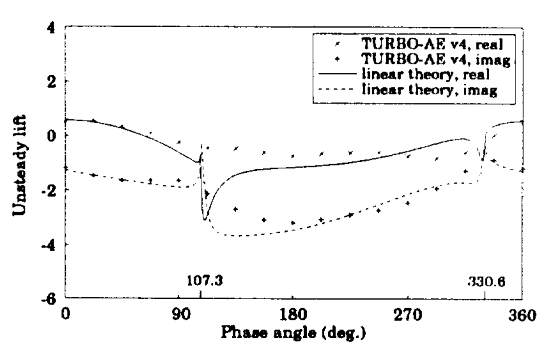
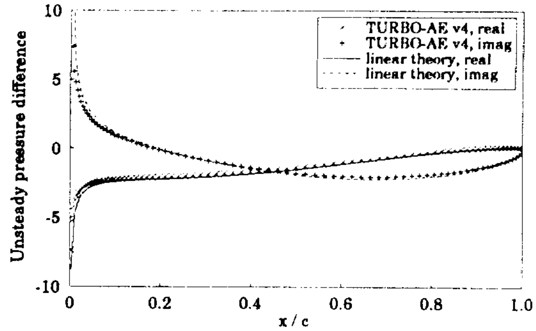
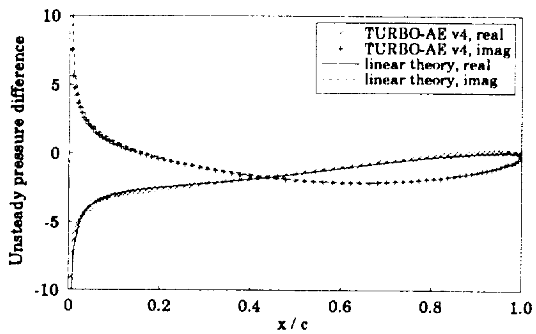


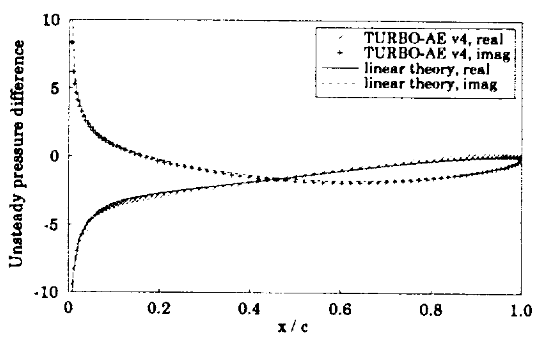
Figure 4: Unsteady lift for plunging motion.



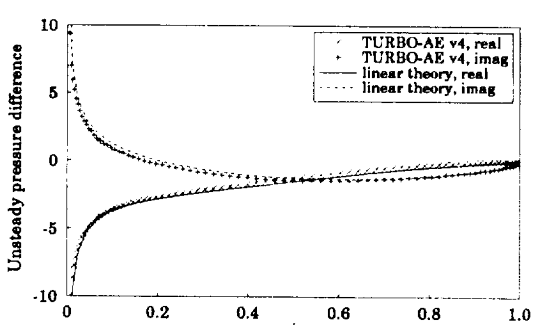
(a) 0 deg. pitching



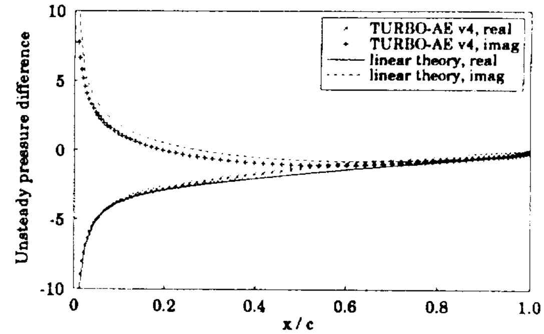
(b) 22.5 deg. pitching



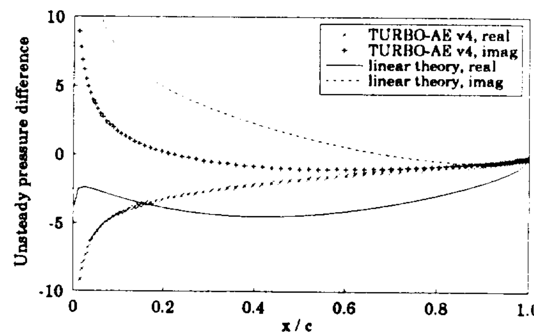
(c) 45 deg. pitching



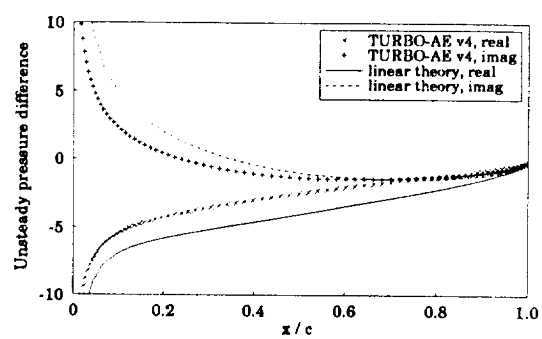
(d) 67.5 deg. pitching



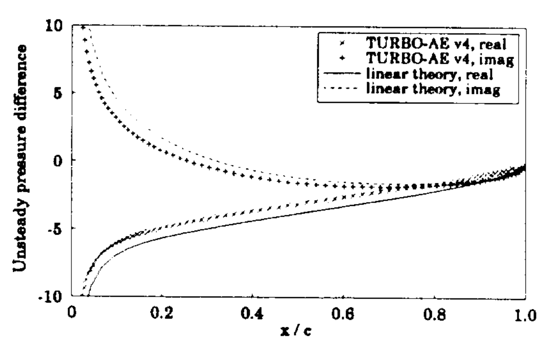
(e) 90 deg. pitching



(f) 112.5 deg. pitching

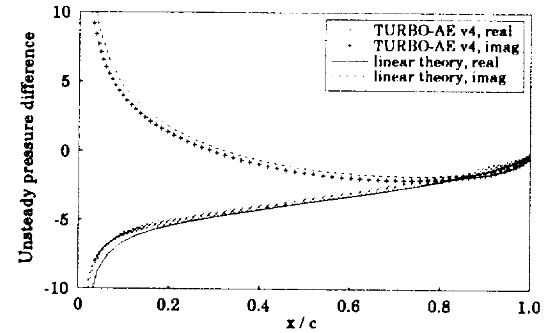


(g) 135 deg. pitching

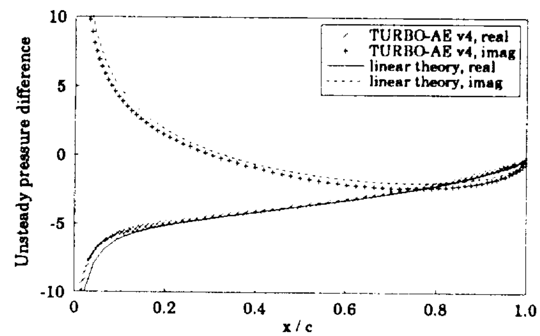


(h) 157.5 deg. pitching

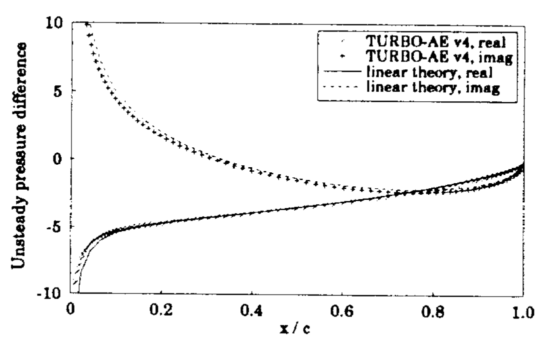
Figure 5: Unsteady pressure difference (first harmonic) for pitching motion.



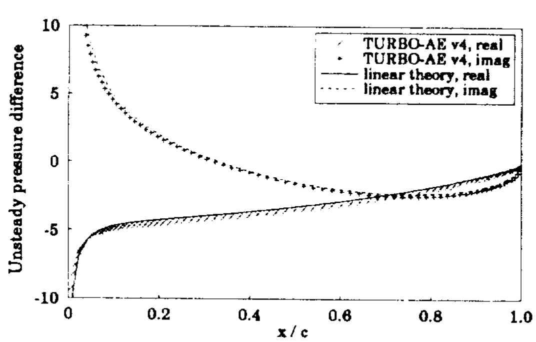
(i) 180 deg. pitching



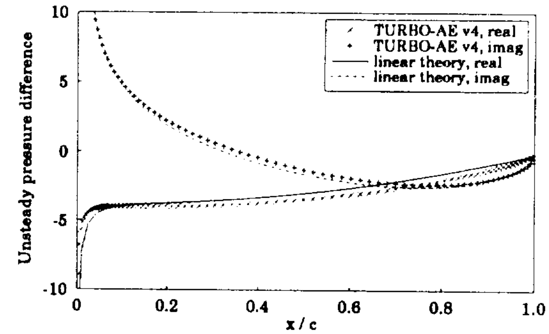
(j) 202.5 deg. pitching



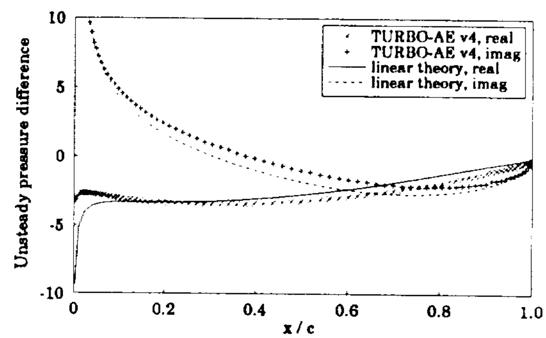
(k) 225 deg. pitching



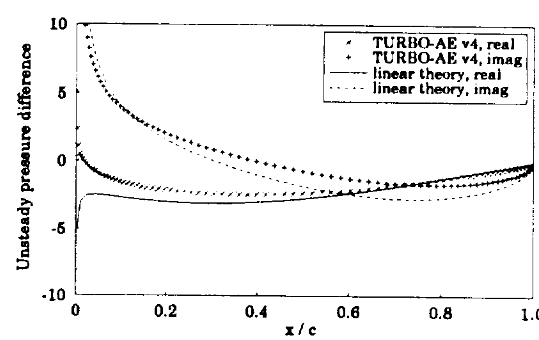
(l) 247.5 deg. pitching



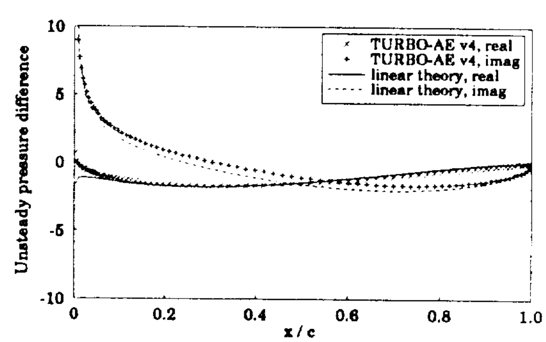
(m) 270 deg. pitching



(n) 292.5 deg. pitching

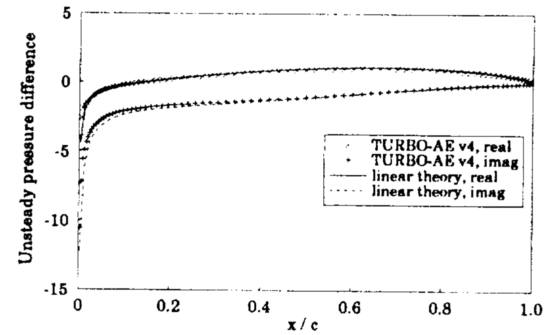


(o) 315 deg. pitching

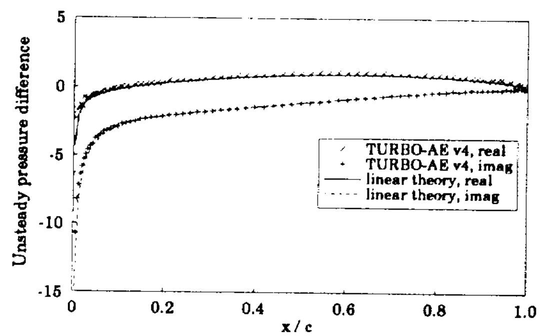


(p) 337.5 deg. pitching

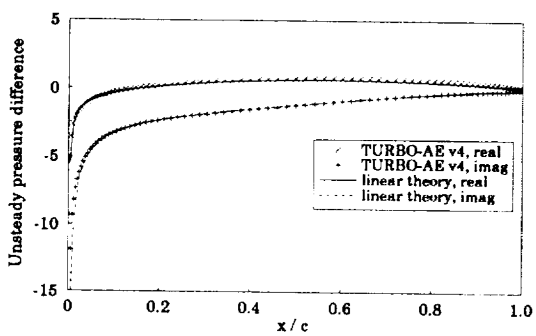
Figure 5 (continued): Unsteady pressure difference (first harmonic) for pitching motion.



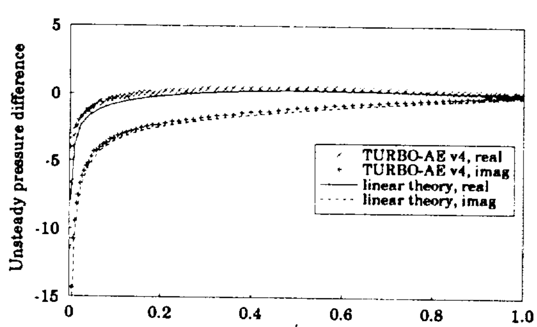
(a) 0 deg. plunging



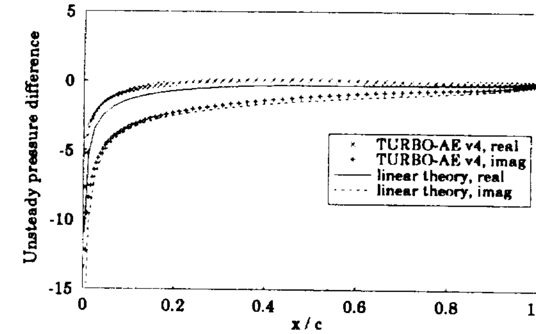
(b) 22.5 deg. plunging



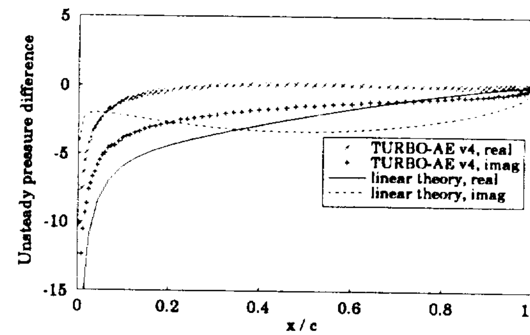
(c) 45 deg. plunging



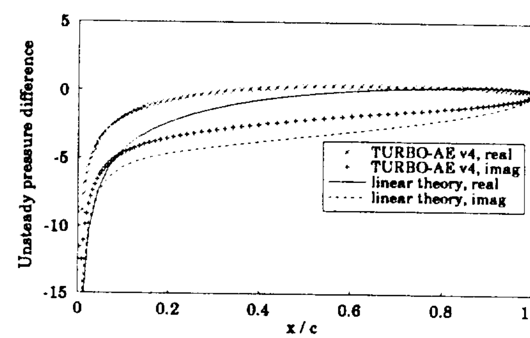
(d) 67.5 deg. plunging



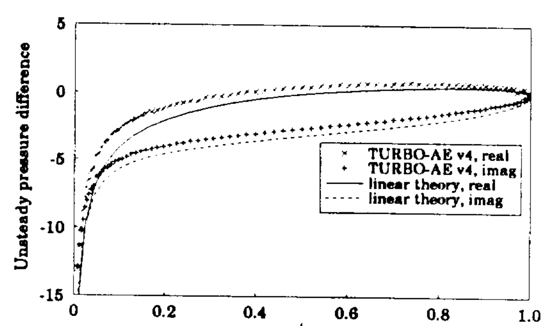
(e) 90 deg. plunging



(f) 112.5 deg. plunging

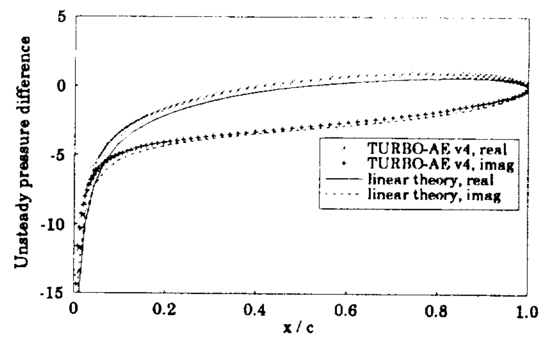


(g) 135 deg. plunging

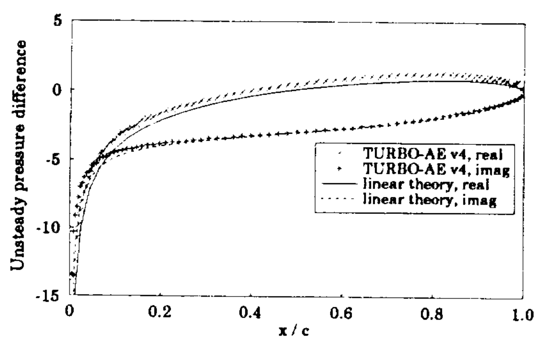


(h) 157.5 deg. plunging

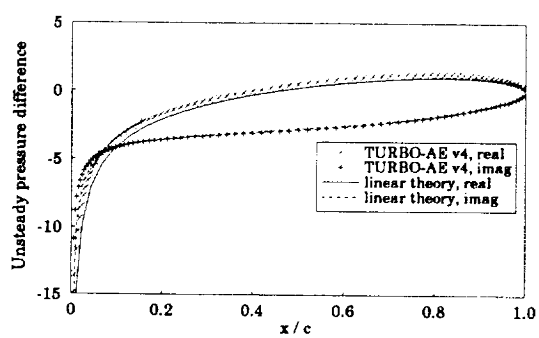
Figure 6: Unsteady pressure difference (first harmonic) for plunging motion.



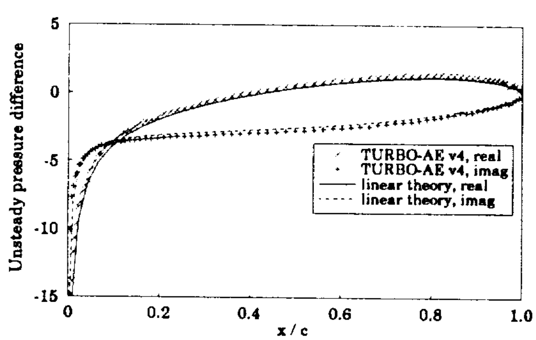
(i) 180 deg. plunging



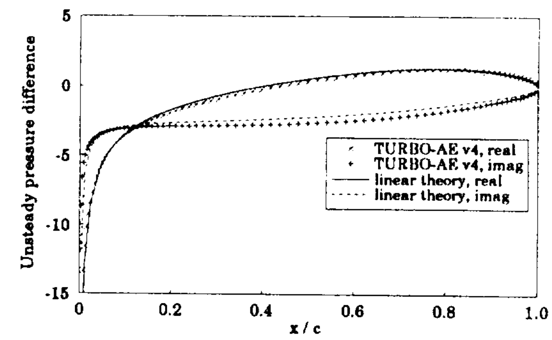
(j) 202.5 deg. plunging



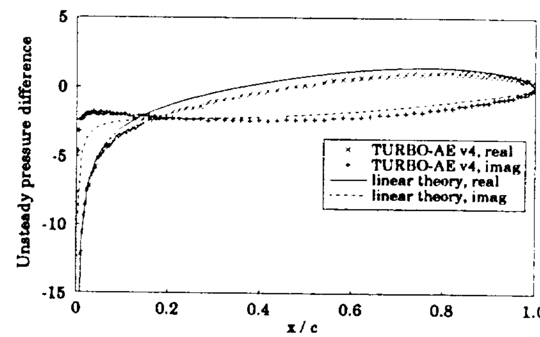
(k) 225 deg. plunging



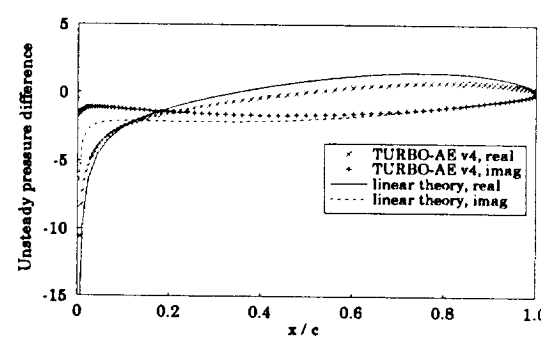
(l) 247.5 deg. plunging



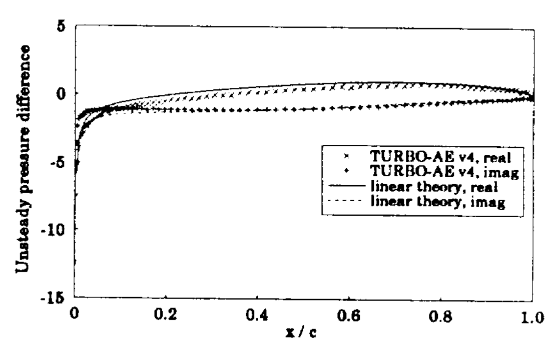
(m) 270 deg. plunging



(n) 292.5 deg. plunging



(o) 315 deg. plunging



(p) 337.5 deg. plunging

Figure 6 (continued): Unsteady pressure difference (first harmonic) for plunging motion.

Appendix B

UNSTEADY AERODYNAMIC MODELING OF BLADE VIBRATION USING THE TURBO_V3.1 CODE

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George L. Stefko ***
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Cleveland, Ohio 44135

Abstract

This report presents representative unsteady aerodynamic results for blade vibration from the Euler / Navier-Stokes unsteady aerodynamic code TURBO_V3.1. Unsteady pressure, lift, and moment distributions are presented for a helical fan test configuration that is used to verify the code by comparison to two-dimensional linear potential (flat plate) theory. The results are for pitching and plunging motions over a range of phase angles. Good agreement with linear theory is seen for all phase angles except those near acoustic resonances. The agreement is better for sub-resonant conditions than for super-resonant conditions.

Introduction

There is an ongoing effort to develop technologies to increase the fuel efficiency of commercial aircraft engines, improve the safety of engine operation, reduce the emissions, and reduce engine noise. With the development of new designs of ducted fans, compressors, and turbines to achieve these goals, a basic aeroelastic requirement is that there should be no flutter or high resonant blade stresses in the operating regime. In order to verify the aeroelastic soundness of the design, an accurate prediction of the unsteady aerodynamics and structural dynamics of the propulsion component is required. Computational aeroelastic modeling of fans, compressors, and turbines requires many simplifying assumptions. Typically, flutter calculations assume that the blade row is isolated. This simplifies the structural dynamics formulation and the unsteady aerodynamic calculations considerably.

For aeroelastic problems in which viscous effects play an important role (such as flutter with flow separation, or stall flutter, and flutter in the presence of shock and boundary-layer interaction), an advanced aeroelastic computational capability is required. The authors of this report have earlier presented [1] some results from the TURBO-AE aeroelastic code. Initial calculations were restricted to in-phase (zero phase angle) blade motions and inviscid flow. In a later paper [2], results were presented for zero and non-zero phase angle motions and viscous flow. In these calculations, multiple blade passages were modeled for non-zero phase angle motions. More recently [3], results have been presented using a single blade passage with phase-lag periodic boundary conditions to model arbitrary phase angle motions. Most recently [4], results for the helical fan configuration have been presented over a range of phase angles; the helical fan configuration has been used as a basic test case to allow code verification by direct comparison with two-dimensional linear theory. All the previously referenced work has been done with the TURBO-AE code, which is based on an unsteady aerodynamic Euler / Navier-Stokes code (TURBO), developed separately [5,6] with the inlet/exit boundary conditions as described in [7,8].

In the present report, the new TURBO_V3.1 code is used along with a pre-processor for blade vibration calculations. The intent of this report is to verify the unsteady aerodynamics modeling capability in the TURBO_V3.1 code for blade vibration. Unsteady pressure, lift, and moment distributions results are presented for blade vibration over a range of phase angles. For non-zero phase angle motions, phase-lag periodic boundary conditions, based on the direct-store method, are used. The 3D non-reflecting inlet/exit boundary conditions [7,8] are not currently implemented in TURBO_V3.1. A helical fan configuration is used. The geometry and flow conditions are chosen to minimize non-linear and three-dimensional effects since the intent is to verify the code by comparison with two-dimensional linear potential (flat plate) theory.

TURBO_V3.1 Unsteady Aerodynamic Code

The TURBO code was originally developed [5] as an inviscid flow solver for modeling the flow through turbomachinery blade rows. Additional developments were made [6] to incorporate viscous effects into the model. This Reynolds-

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averaged Navier-Stokes unsteady aerodynamic code is based on a finite volume scheme. Flux vector splitting is used to evaluate the flux Jacobians on the left-hand side of the governing equations [5] and Roe's flux difference splitting is used to form a higher-order TVD (Total Variation Diminishing) scheme to evaluate the fluxes on the right hand side. Newton sub-iterations are used at each time step to maintain higher accuracy. Symmetric Gauss-Seidel iterations are applied to the discretized equations. A Baldwin-Lomax algebraic turbulence model is used for viscous flows.

Some important differences between TURBO_V3.1 and previous versions of TURBO / TURBO-AE are summarized below. Only those features that are relevant to the blade vibration calculations are listed.

TURBO / TURBO-AE	TURBO_V3.1
Blade vibration capability is present in TURBO-AE.	Blade vibration capability requires pre-processor.
Frame of reference is fixed or rotating depending on input flag; only fixed frame is used for blade vibrations.	Frame of reference is rotating with blade row.
3D non-reflecting inlet/exit boundary conditions [7,8] are implemented in TURBO-AE.	3D non-reflecting inlet/exit boundary conditions [7,8] are not implemented.
Phase-lag periodic boundary conditions are implemented with direct-store method or Fourier-decomposition (shape-correction) method.	Phase-lag periodic boundary conditions are implemented with direct-store method with under-relaxation option.
Grid input is in right-handed coordinate system.	Grid input is in left-handed coordinate system.
Input/output is referenced to inlet static or total conditions depending on input flag.	Input/output is referenced to inlet total conditions.

Results

Results are presented which serve to verify the unsteady aerodynamic modeling capability in the TURBO_V3.1 code for blade vibration. The test configuration selected is a helical fan [7]. This configuration consists of a rotor with twisted flat plate blades enclosed in a cylindrical duct with no tip gap. This configuration was developed by researchers [7] to provide a relatively simple test case for comparison with two-dimensional analyses. The geometry is such that three-dimensionality of the flow is minimized.

The parameters of this three-dimensional configuration are such that the mid-span location corresponds to a flat plate cascade with a stagger angle of 45 deg. and unit gap-to-chord ratio operating in a uniform mean flow at a Mach number of 0.7 parallel to the blades. The rotor has 24 blades with a hub/tip ratio of 0.8. The inlet flow (axial) Mach number used in this calculation is 0.495, which results in a relative Mach number of approximately 0.7 at the mid-span section. The results presented are obtained from inviscid runs of the TURBO_V3.1 code.

The grid used for the calculations is $141\times11\times41$ in one blade passage. On each blade surface, 81 points are located in the chordwise direction and 11 points in the spanwise direction. The inlet and exit boundaries are located at an axial distance of approximately 0.7 chord lengths from the blade leading and trailing edges. To begin, a steady solution is obtained for this configuration. The steady flowfield consists of uniform flow at each radial location.

Aeroelastic calculations are performed starting from the steady solution. Calculations have been performed for harmonic blade vibration in plunging and pitching modes, separately, for phase angles of 0, 30, 60, ... , and 330 deg. The pitching is about the mid-chord. The prescribed mode shapes are such that the amplitude of vibration does not vary along the span. This choice of mode shapes is meant to reduce the three-dimensionality of the unsteady flowfield for ease of comparison with two-dimensional analyses.

The vibration frequency is selected so that the non-dimensional reduced frequency based on blade chord is 1.0 at the mid-span. In previous papers [3,4], results were presented to show the sensitivity of computations to the number of time steps used in each cycle of blade vibration. Calculations were done with the TURBO-AE code for 100, 200, and 300 time steps per cycle of vibration for 0 deg. phase angle plunging motion. The time step was varied so as to keep the vibration time period (or frequency) fixed. The unsteady pressure and work-per-cycle results for 200 and 300 time steps per cycle were shown to be nearly identical. Based on such calculations with the TURBO-AE code, it was determined that 200 time steps per cycle provided adequate temporal resolution for the selected vibration frequency. All results presented here with the TURBO_V3.1 code have been obtained using 200 time steps per cycle.

The non-dimensional time step used in the calculations (with 200 time steps per cycle) is 0.046, which results in a maximum CFL number of 61.3. The amplitude of blade vibrations in the calculation is a pitching amplitude of 0.02 deg. or a plunging amplitude of 0.01% chord. In all cases, calculations were continued for 20 cycles of blade vibration to allow the flowfield to become periodic. The exceptions were the cases of zero phase angle for which 10 cycles of blade vibration were used.

Figure 1 shows the unsteady moment about mid-chord (in complex form) for pitching blade motion about the mid-chord. These results are from the mid-span location and were calculated using the first harmonic of the unsteady blade surface pressure difference. Semi-analytical results from two-dimensional linear potential (flat plate) theory [9] are included for comparison.

The overall level of agreement between TURBO_V3.1 results and linear theory is good, with exceptions to be discussed in the following paragraph. For subsonic flows and small amplitude of blade motions, it is expected that there will be no significant difference between the Euler and linear potential results. Hence, the observed agreement is not surprising and provides a basic verification of the TURBO_V3.1 code. It may be noted that the parameters of the present configuration were selected [7] to allow precisely this type of verification by comparison to two-dimensional analyses.

In Fig. 1, some deviation from linear theory is seen in the results for the phase angles of 120 and 330 deg. Both these phase angles fall near conditions of acoustic resonance (or cut-off conditions) in the corresponding two-dimensional flat plate cascade. The acoustic resonances occur at phase angles of 107.3 and 330.6 deg.; these values are marked on the phase angle axis of Fig. 1 for reference. The phase angles between these resonances are associated with sub-resonant [10] (cut-off) conditions in which all disturbances attenuate away from the cascade. No disturbances propagate in the upstream or downstream directions under sub-resonant conditions. The phase angles between 0 and 107.3 deg. and between 330.6 and 360 deg. are associated with super-resonant (cut-on) conditions in which at least one disturbance propagates in either the far upstream or downstream direction.

The significance of the sub-resonant and super-resonant conditions to computational aeroelasticity can be explained as follows. Since the typical computational domain does not extend very far from the blade row or cascade, the inlet/exit boundary conditions must minimize (or eliminate) the reflection of disturbances generated by the vibration of the blades. For sub-resonant conditions, it may be possible to reduce the reflected disturbances by moving the boundary farther away from the blade row. This is not possible for super-resonant conditions. From Fig. 1, it can be seen that the results from TURBO_V3.1 agree well with linear theory for sub-resonant conditions, but not as well for super-resonant conditions. This difference in the level of agreement is related to the inlet/exit boundary conditions. As mentioned earlier, the 3D non-reflecting inlet/exit boundary conditions [7,8] have not been implemented in TURBO_V3.1. The results of previous calculations with the TURBO-AE code [4] with the 3D non-reflecting inlet/exit boundary conditions have shown a better level of agreement for super-resonant conditions for the same configuration with the same grid.

Figure 2 shows the unsteady lift (in complex form) for plunging blade motion. As noted for the pitching results, these results are also from the mid-span location and were also calculated using the first harmonic of the unsteady blade surface pressure difference. Results from linear potential theory are included in Fig. 2 for comparison. The overall level of agreement with linear theory is good. Deviations are observed close to the acoustic resonances, as for pitching. The level of agreement is better for sub-resonant conditions than it is for super-resonant conditions.

Figure 3 shows the unsteady blade surface pressure difference (first harmonic) at the mid-span location for pitching blade motion about the mid-chord. Results are presented for phase angles values between 0 and 360 deg. in steps of 30 deg. In each case, the linear theory results are included for comparison. In most cases, the agreement with linear theory is very good. The exceptions occur at phase angles near acoustic resonance conditions, as noted earlier in the description of the unsteady moment (Fig. 1). It is worth noting that, in this case, the integrated results in Fig. 1 accurately represent the level of agreement with linear theory, without obscuring any differences in the details of the pressure distributions.

Figure 4 shows the unsteady blade surface pressure difference (in complex form) for plunging blade motion. The level of agreement with linear theory is good, as reflected in the unsteady lift (Fig. 2). Deviations from linear theory are restricted to the phase angles near conditions of acoustic resonance.

Note that all the TURBO_V3.1 results presented are the first harmonic components of the unsteady variations. The higher harmonics are extremely small for these calculations, indicating the linearity of the unsteady flow. Previous results [2] had shown a nonlinear dependence on amplitude for certain cases for pitching amplitudes of blade vibration of 2 deg., but not at the 0.02 deg. amplitude used in the present calculations. The deviations in the regions of acoustic resonances may possibly be reduced by the use of finer grids. But, such a grid refinement study has not been performed.

Concluding Remarks

The unsteady aerodynamic modeling capability in the TURBO_V3.1 code for blade vibration has been verified. The verification has been done by running the code for a helical fan test configuration. Results have been presented for pitching and plunging blade motions over a range of phase angles. The results compare well with results from a linear potential analysis. This agreement is expected for subsonic flows for which the calculations were made and for the relatively small amplitudes of blade motion. Some deviations are observed for values of phase angles near acoustic resonance conditions. Also, the agreement is not as good for super-resonant conditions as it is for sub-resonant conditions. This difference is due to the inlet/exit boundary conditions, which reflect some disturbances back into the computational domain. It is expected that such reflections will be significantly reduced when the 3D non-reflecting inlet/exit boundary conditions [7,8] are implemented in a future version of the TURBO_V3.1 code. Overall, the helical fan test case provides a basic verification of the unsteady aerodynamic modeling for blade vibration with the TURBO_V3.1 code.

It is necessary to further verify the unsteady aerodynamic modeling capability in the TURBO_V3.1 code using different standard test configurations to compare with experimental data and other code predictions. Also, it is necessary that the TURBO_V3.1 code be exercised to evaluate its ability to analyze and predict flutter for conditions in which viscous effects are significant.

Acknowledgments

The authors would like to gratefully acknowledge the support of Project Managers Peter G. Batterton (Subsonic Systems Office) and John E. Rohde (Advanced Subsonic Technology Project Office) at NASA Lewis Research Center. Computational resources for this research were provided by NAS.

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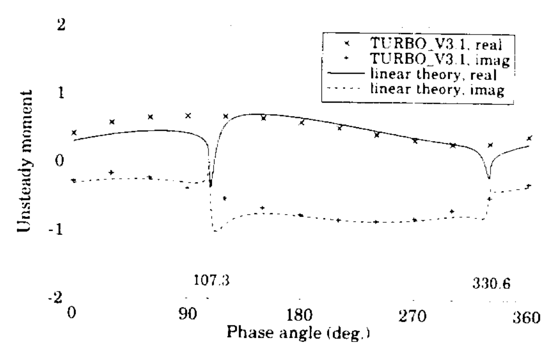


Figure 1: Unsteady moment for pitching motion.

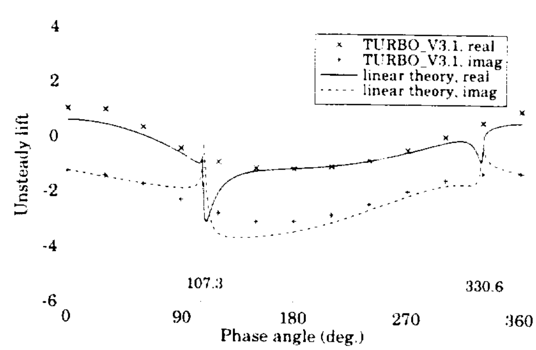


Figure 2: Unsteady lift for plunging motion.

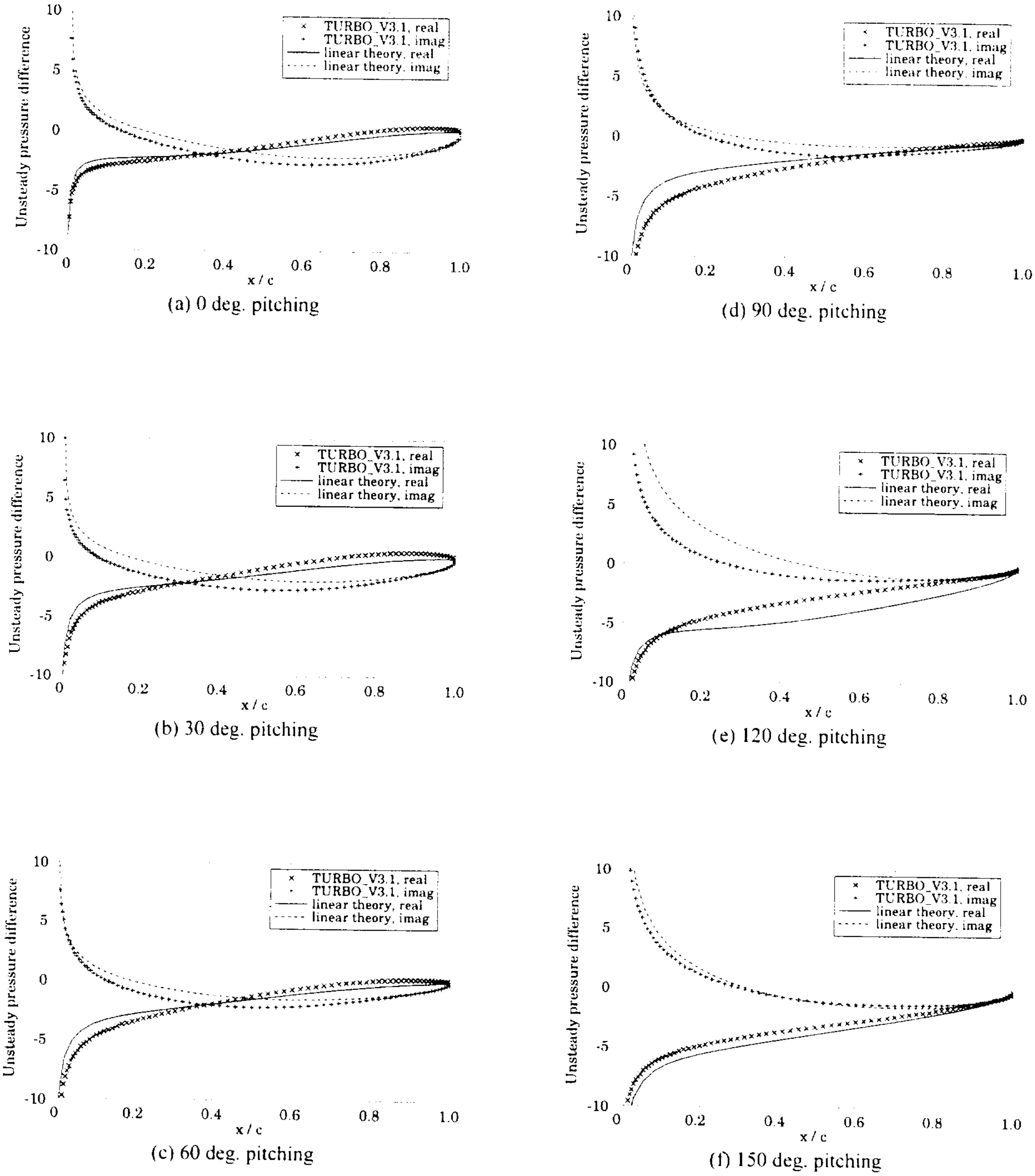
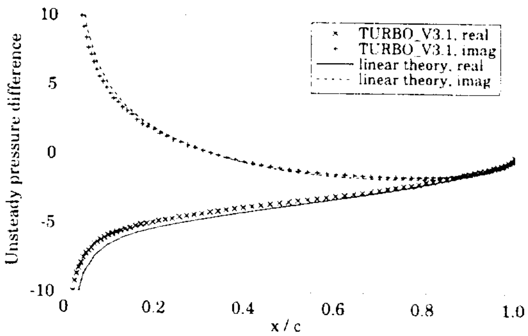
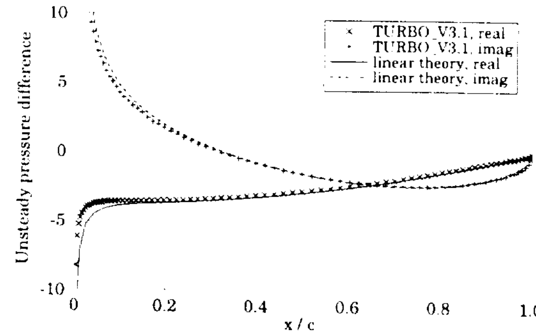


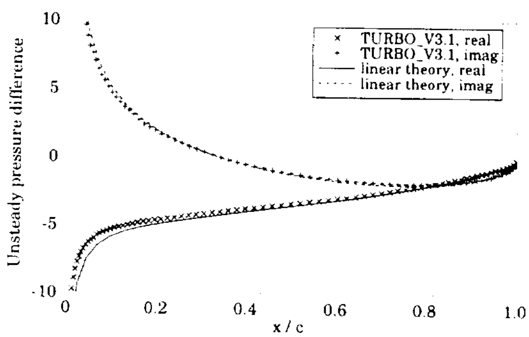
Figure 3: Unsteady pressure difference (first harmonic) for pitching motion.



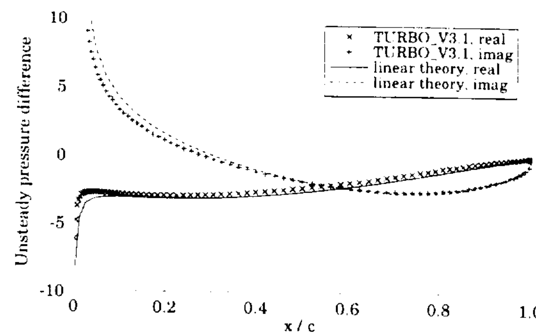
(g) 180 deg. pitching



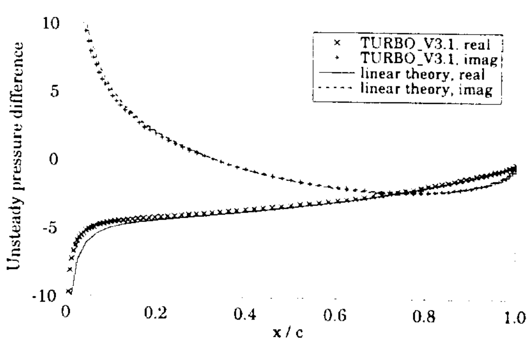
(j) 270 deg. pitching



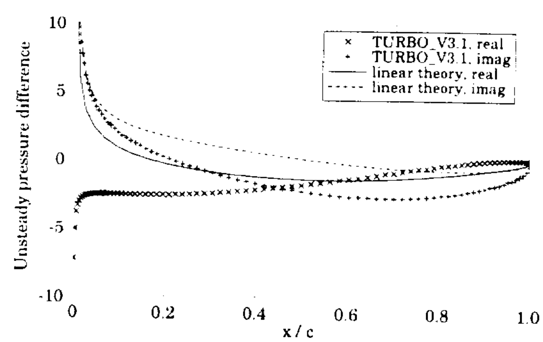
(h) 210 deg. pitching



(k) 300 deg. pitching

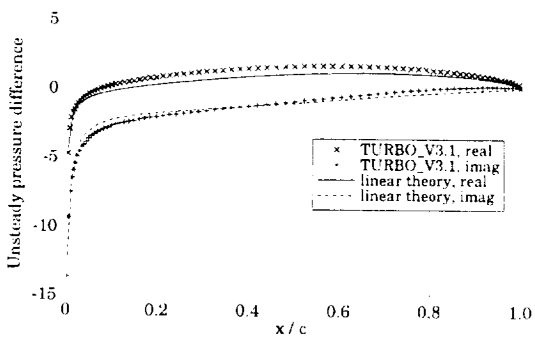


(i) 240 deg. pitching

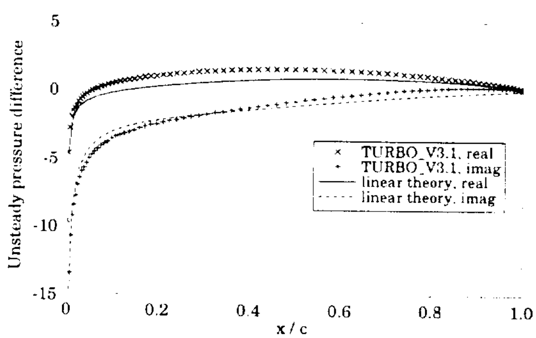


(l) 330 deg. pitching

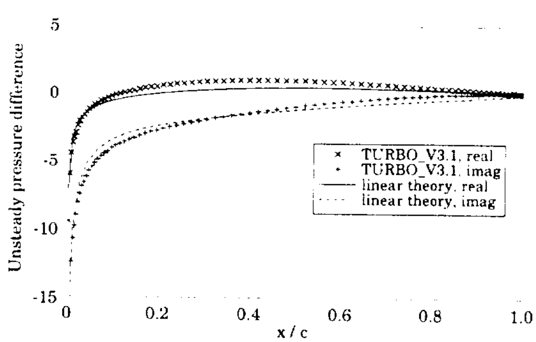
Figure 3 (continued): Unsteady pressure difference (first harmonic) for pitching motion.



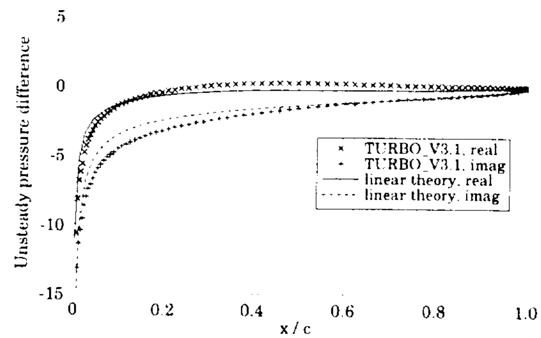
(a) 0 deg. plunging



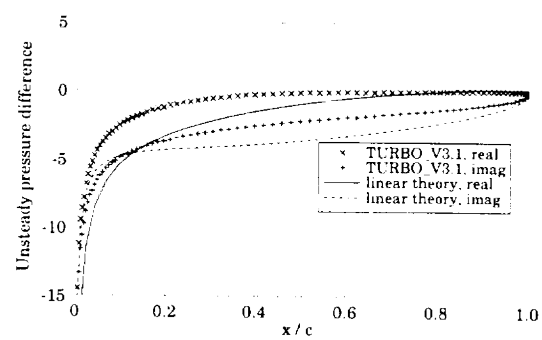
(b) 30 deg. plunging



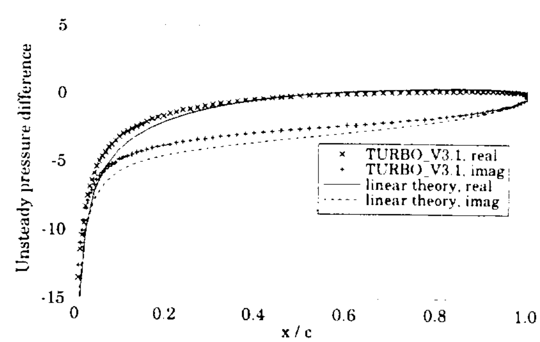
(c) 60 deg. plunging



(d) 90 deg. plunging

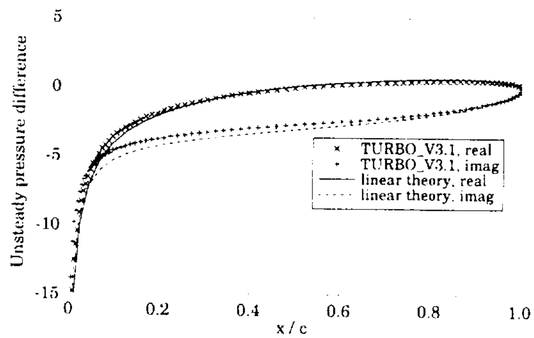


(e) 120 deg. plunging

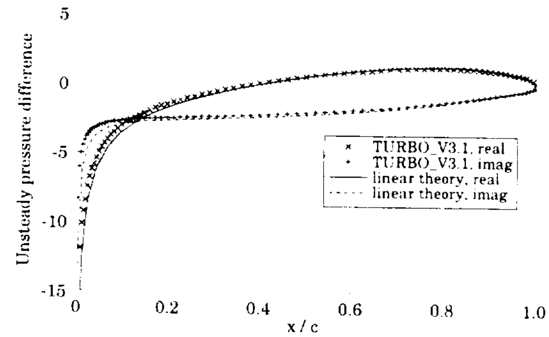


(f) 150 deg. plunging

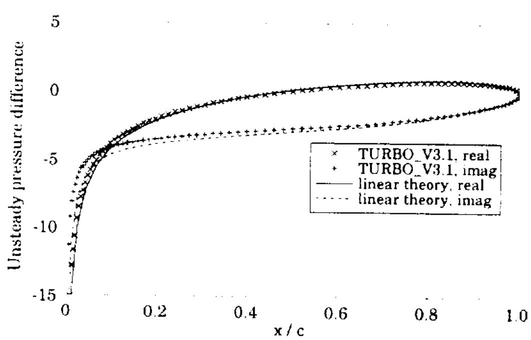
Figure 4: Unsteady pressure difference (first harmonic) for plunging motion.



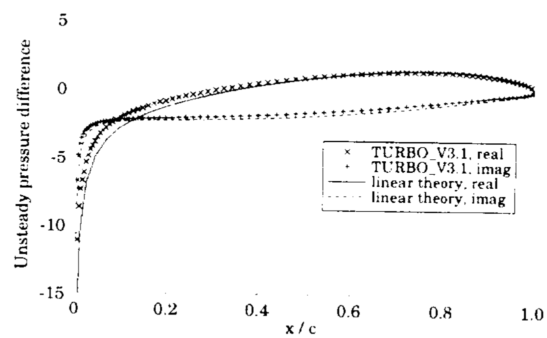
(g) 180 deg. plunging



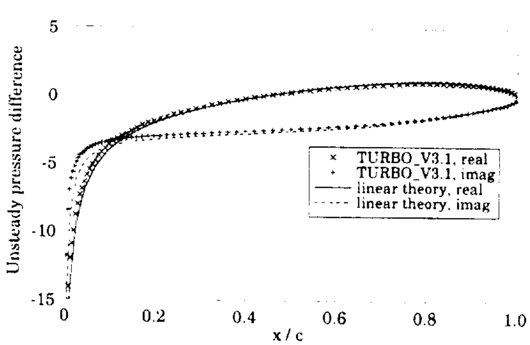
(j) 270 deg. plunging



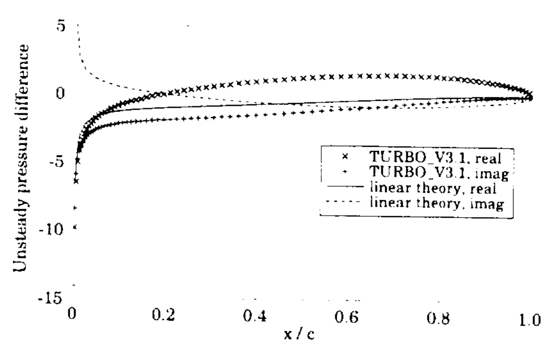
(h) 210 deg. plunging



(k) 300 deg. plunging



(i) 240 deg. plunging



(l) 330 deg. plunging

Figure 4 (continued): Unsteady pressure difference (first harmonic) for plunging motion.