Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-50-TR-2009/069 December 2009

Hydromechanics Department Report

Evaluation and Improvement of the PBD-X/MTFLOW Propulsor Analysis Software

by

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20100115018

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
December 2009	Final	05/2009 - 09/2009

4. TITLE AND SUBTITLE
Evaluation and Improvement of the PBD-X/MTFLOW Propulsor Analysis Software

5a. CONTRACT NUMBER
N0001409WX21237

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Thad J. Michael

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
09-1-5800-320

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Naval Surface Warfare Center
Carderock Division
9500 Macarthur Boulevard
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-50-TR-2009/069

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Attn ONR 331
Chief of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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A postprocessor for PBD-X has been written to create the input files for BSHAPE, a blade shape design program developed for use with PBD-14. This will support the creation of a design capability using PBD-X. MTSET, the grid generation component of MTFLOW, has been modified to include additional grid spacing options. This will greatly improve the usability of MTSET and the quality of the throughflow grids while maintaining the current ease of use.

15. SUBJECT TERMS
PROPULSOR, HYDRODYNAMICS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Thad J. Michael
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	40	19b. TELEPHONE NUMBER *(include area code)* (301)227-5831

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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NOMENCLATURE

GAMMA	Non-dimensional circulation
MKEY	Number of spanwise points used to construct the vortex lattice
R	Radius non-dimensionalized by tip radius or inlet radius
Vt	Tangential velocity non-dimenionalized by free-stream velocity or mean inlet velocity
X	Axial coordinate non-dimensionalized by tip radius or inlet radius

ABBREVIATIONS

MIT	Massachusetts Institute of Technology
NSWCCD	Naval Surface Warfare Center, Carderock Division
ONR	Office of Naval Research
RANS	Reynolds-Averaged Navier-Stokes
RPM	Revolutions per minute

ABSTRACT

The software suite PBD-X/MTFLOW has been exercised for evaluation with both waterjet pumps and open propellers. PBD-X is a lifting surface propeller analysis code for steady conditions. MTFLOW is an axisymmetric Euler solver used to solve the axisymmetric component of the flow field inside of a waterjet pump or in and around a propeller.

The results of the PBD-X/MTFLOW calculations were compared with PBD-14/MTFLOW calculations. PBD-14 is an earlier lifting surface code which uses a different formulation for determining the effective wake when coupled with MTFLOW. It was found that PBD-X produces almost identical results to PBD-14 for open propellers when coupled with MTFLOW.

For waterjet pumps, PBD-X predicts significantly less circulation. The reason for this difference is not known. However, it may be related to the different formulation used in PBD-X which improves convergence for waterjet pumps. Because past PBD-14 predictions for waterjet pumps have not been accurate, it is hoped that the predictions from PBD-X will be better. However, further development of PBD-X is required before more detailed conclusions can be made.

A postprocessor for PBD-X has been written to create the input files for BSHAPE, a blade shape design program developed for use with PBD-14. This will support the creation of a design capability using PBD-X.

MTSET, the grid generation component of MTFLOW, has been modified to include additional grid spacing options. This will greatly improve the usability of MTSET and the quality of the throughflow grids while maintaining the current ease of use.

ADMINISTRATIVE INFORMATION

This work was sponsored by Dr. Ki-Han Kim, Office of Naval Research (ONR), Code 331. The work was conducted by the Naval Surface Warfare Center, Carderock Division (NSWCCD), Hydromechanics Department, Resistance and Propulsion Division (Code 5800) under work unit number 09-1-5800-302.

INTRODUCTION

This report describes the evaluation and improvements made to the PBD-X/MTFLOW software for the analysis of open propellers, ducted propellers, and waterjet pumps. PBD-X is a vortex lattice propeller analysis code in development by Professor Justin Kerwin of the Massachusetts Institute of Technology (MIT). MTFLOW is an axisymmetric Euler solver previously developed by Professor Mark Drela of MIT.

The first objective of this effort was to validate the software by computing open propellers and waterjet pumps and comparing the results with the predictions of the existing vortex lattice code, PBD-14 [1], with which the Navy has a substantial experience base. The second objective was to make improvements to the software based on the findings of the evaluation effort and input from users of the software.

This report is divided into two primary sections, evaluation and improvements.

BACKGROUND

PBD-14 is a vortex lattice propeller design and analysis code developed at MIT and currently in use at the Naval Surface Warfare Center, Carderock Division (NSWCCD) [1]. For this evaluation, PBD-14n was used, which includes modifications by NSWCCD.

PBD-X builds on the success of PBD-14, but uses a different decomposition for the velocity field; one which is better suited to waterjet pumps [2]. For the axial and radial velocity components, PBD-X computes total velocity at the blade surface as the sum of the circumferential mean velocity from MTFLOW and the local velocity variation (not including the mean) induced by the vortex lattice. The tangential total velocity component at the blade surface is computed by convecting the upstream tangential velocity through the blade row and adding the local velocity (including the mean) induced by the vortex lattice.

The current version of PBD-X models hubs and ducts using images, like PBD-14. A future version will use source panels to enforce the kinematic boundary condition on the hub and duct. PBD-X does not yet compute forces.

To compare predictions, features in PBD-14 that are not available in PBD-X were deactivated. These include thickness, viscous drag, and wake alignment. In PBD-X the wake follows the circumferential mean velocities from MTFLOW. With wake alignment deactivated, PBD-14 uses a similar method.

PBD-14 can be coupled with MTFLOW for the design and analysis of propulsors [3,4], but it can also be run in a stand-alone mode. PBD-X requires coupling with MTFLOW. MTFLOW handles the calculation of the throughflow in the case of waterjets and ducted

propellers. For open propellers, MTFLOW is also used to compute the axisymmetric flow field although it is typically much simpler than in the other cases. MTFLOW solves the flow field on a grid which is iteratively aligned with the flow; it follows streamtubes.

The initial grid for the MTFLOW solution is generated by the code MTSET. MTSET uses the geometry of the hub and duct, or "elements," to create a distribution of nodes on the surfaces. Combined with an estimated stream function, an initial grid is created and elliptically smoothed.

EVALUATION OF PBD-X

PBD-X was evaluated by computing three open propeller and two waterjet pump geometries and comparing the results with PBD-14 calculations. A uniform flow field was used at the far upstream boundary. In the case of waterjet stator blades, a rotor solution from a previous calculation was used to create the inflow to the stator blades.

The two waterjet pumps are axial flow designs funded by ONR for the purpose of scientific measurements and calculations. The three propellers are model propellers which have been used for scientific measurements and calculations in the past.

AXWJ-2

The ONR AxWJ-2 is a recent axial flow waterjet pump design completed at NSWCCD and described in [5]. Computations were made at the design advance coefficient based on mean inlet velocity, 1.19. This corresponds to the design flow coefficient of 0.85.

Rotor

The MTFLOW mesh is shown in Figure 1 with the swept 16×17 rotor blade lattice and 21×20 stator blade lattice. The stator was not computed by PBD-X or PBD-14. An MTFLOW option to automatically cancel swirl was added some time ago and used for this evaluation. All tangential velocity is cancelled at the trailing edge of the stator blade. In this way, the rotor calculations are independent of any stator calculations.

First, several convergence studies were made to determine appropriate lattice densities and spacings, and numbers of images for the subsequent calculations. The spanwise circulation distribution and downstream tangential velocity distributions were compared. The effect of changing the number of images is shown in Figures 2 and 3. It was found that the number of images should be at least 75% of MKEY, the spanwise dimension of the vortex lattice.

The effect of changing the spanwise lattice dimension, MKEY, is shown in Figures 4 and 5 for spanwise cosine and uniform spacings, respectively. An MKEY value of 17 was found to be sufficient for this case with both spacings.

Figure 6 compares the predicted spanwise circulation and downstream tangential velocity from PBD-X with predictions from PBD-14. The PBD predictions do not match. PBD-X predicts less circulation, therefore less thrust and torque, than PBD-14. This disagreement is most likely due to the different methods of computing the local total velocities that are used in each of the codes. The PBD-14 method may introduce errors when the mean induced velocities are a large fraction of the total.

Figure 7 shows the difference in the predicted chordwise loading at midspan between PBD-X and PBD-14. It appears that the difference is a constant fraction of the loading, except for a small difference in shape at the leading edge. It was found that the PBD-14 prediction adds 3.3% more energy to the flow than PBD-X.

To assess the importance of wake alignment for this configuration, PBD-14 was also run with wake alignment turned on. The effect was small for cosine spanwise spacing with MKEY=17, as shown in Figure 8. It was found that with uniform spanwise spacing, at least MKEY=20 was required for the PBD-14 results with wake alignment to be independent of MKEY. But the overall effect of wake alignment was small.

PBD-X generates different vortex lattices than PBD-14n, particularly for the images. PBD-14n was modified from the original MIT version of PBD-14 to place images at the same axial location as the vortex segment being imaged. PBD-X, like the original PBD-14, places the images at the same axial location as the tip or root of the blade, depending on whether they are hub images or casing images. The different lattices are overlaid in Figure 9. Fortunately, the effect of the different lattices was found to be small. Figure 10 shows the effect of importing the PBD-14 lattices, blade, wake, and images, into PBD-X.

Stator

To make the stator calculations independent of the rotor calculations, the circumferential average velocity at a plane between the rotor and stator from the Reynolds-Averaged Navier-Stokes (RANS) design calculations using CFX [5] was used as the basis for the inflow to the stator. Figure 11 compares the CFX computed velocity distribution with the inflow used in the PBD/MTFLOW calculations.

Convergence of the number of spanwise vortex elements was checked first. Figure 12 shows that the value MKEY=17 used for the rotor was also sufficient for the stator.

Comparing the PBD-X and PBD-14 spanwise circulation distributions, shown in Figure 13, revealed a different shape. Loading the PBD-14 blade, wake, and image lattices into PBD-X demonstrated that the difference was due to the PBD-X lattice, as shown in Figure 14. Figure 15 compares the PBD-X lattice with the PBD-14 lattice. The length of the wake from PBD-X appears to be much longer than from PBD-14. This is because PBD-X uses a different method of determining the wake length than PBD-14. Professor Kerwin notes that he has focused on developing PBD-X for rotors at this point and not stators.

AXWJ-1

The ONR AxWJ-1 is an axial flow waterjet pump designed at NSWCCD and described in [6]. The design was completed with PBD-14/MTFLOW. RANS was not used during the design. Computations were made at the design advance coefficient based on mean inlet velocity, 0.61. These calculations were used to provide a second point of comparison for waterjet pumps. Figure 16 shows the MTFLOW mesh with the blade lattices overlaid.

Rotor

Convergence studies supported the conclusions from the AxWJ-2 study. A comparison of the spanwise circulation distribution predicted by PBD-14 and PBDX also had similar results, as shown in Figure 17. The effect of advance coefficient, or flow coefficient, was investigated. Figure 18 shows that the difference between the PBD-14 and PBD-X results is larger when the rotor loading is increased at lower advance coefficients. A comparison of the chordwise circulation distributions at midspan was similar to the AxWJ-2 results, even though the AxWJ-1 chordwise loading distribution is significantly different, as shown in Figure 19. It was found that the PBD-14 prediction adds 6.3% more energy to the flow than PBD-X at the design conditions.

Using the PBD-14 lattice geometry in PBD-X had little effect for the rotor calculations, whether only the blade lattice or all lattices were imported into PBD-X.

Stator

For stator calculations, the stator inflow computed with PBD-14 at a rotor advance coefficient of 0.80, shown in Figure 20, was used for all calculations. A sensitivity study showed that the spanwise number of lattice elements was converged at 17 with cosine spacing. However, with uniform spacing, although the circulation was converged, the downstream tangential velocity was not. Figure 21 shows these results.

Comparing the PBD-14 and PBD-X predicted circulation distributions in Figure 22, they appear almost identical. However, PBD-X predicts less downstream tangential velocity, as with the AxWJ-2 stator.

P4119

Propeller model P4119 is a three-bladed propeller. Computations were made at the design advance coefficient, 0.833. Geometric details can be found in [7].

Often, spanwise half-cosine spacing with the clustering at the tip is used with open propellers. Because PBD-X only supports uniform and full cosine spacing, only those options were evaluated.

At this point, PBD-X development has focused on internal flow problems, not open propellers. For this reason, the streamine-based lattice generation routine in PBD-X did not work well for open propellers. Figure 23 shows how the tip of the blade was cropped by the PBD-X lattice routine. To improve the lattice with minimal effort, automatic tip streamline detection was added to the PBD-X lattice routine. This reduced the amount of the tip that was cropped, but could not eliminate it.

Figure 24 compares the PBD-14 circulation prediction with PBD-X. The effect of the cropped tip is evident in the reduced circulation near the tip in the PBD-X solution. At this point, the PBD-14 lattice was imported into PBD-X. Importing only the blade lattice was sufficient to solve the cropping problem and obtain similar results. Importing all of the lattices (blade, wake, and images) did not have a significant effect on the results. These results are shown in Figure 25. Figure 26 shows that the chordwise circulation distribution at midspan matches when the same lattice is used.

P4381

Propeller model P4381 is a five-bladed propeller. Computations were made at a range of advance coefficients, including the design value, 0.889. Geometric details can be found in [8]. Figure 27 shows the MTSET grid with the PBD-14 lattice geometry.

Again, PBD-X predictions closely matched PBD-14 when the PBD-14 lattice was used. Figure 28 shows the spanwise circulation distribution predicted by both codes over a range of advance coefficients.

P4990

Propeller model P4990 is a five-bladed propeller, representative of modern controllable pitch propeller designs. Computations were made at a range of advance coefficients, including the design value, 1.069. Geometric details can be found in [9]. Figure 29 shows the MTSET grid with the PBD-14 lattice geometry.

Again, PBD-X predictions closely matched PBD-14 when the PBD-14 lattice was used. Figure 30 compares the predicted spanwise circulation distribution and downstream tangential velocity distribution from PBD-14 and PBD-X with a range of lattice sources.

CONCLUSIONS

For open propellers, when the same lattice is used, PBD-X predicts the same circulation distribution as PBD-14. Although there is currently no force prediction from PBD-X, it can be expected to be very close to PBD-14 based on the circulation distributions. The lack of wake alignment and thickness will affect the results.

For waterjet pumps, PBD-X and PBD-14 results are different, even when the same lattice is used. PBD-X is intended to be an improvement over PBD-14 for waterjet pumps, so this is expected. However, until PBD-X is more fully developed it will be difficult to determine if there actually is an improvement, and if so, how much of an improvement. To assess this, a method of computing torque and including viscous drag are required so that pump curves can be plotted. With this information, and an estimate of the effect of thickness and wake alignment from PBD-14, the relative improvement can be assessed.

In the author's opinion, PBD-X seems to converge more rapidly and reliably than PBD-14 for waterjet pumps. For open propellers, there is little difference.

IMPROVEMENTS

Improvements were made to both PBD-X and MTSET based on experience with the evaluation portion of this project and anticipated needs.

PBD-X

In a planned future version, PBD-X will have a design mode. Blade geometry changes will be handled externally by Stephen Neely's BSHAPE program [2]. The BSHAPE program requires certain output files from PBD-14 that PBD-X does not produce, `PBDOUT.IBG` and

PBDOUT.VCP. These files contain the input blade geometry and predicted velocity at the control points.

PBD-X includes a new binary output file which contains most of the input to the code and enough of the output to reconstruct any other required output. To create the files needed by BSHAPE, a postprocessor was written to read the PBD-X binary file and write the files for BSHAPE. This postprocessor is called PBDX2BSHAPE.

It was discovered that the current version of BSHAPE requires that the blade lattice be generated with the PBD-14n lattice generation method developed by Stephen Neely. This method created the lattice using constant parameter values of the B-spline surface. Therefore, the PBD-14n lattice generation routine was added to PBD-X and is available by setting ILAT=2 in the PBD-X input file. It was also necessary to add the B-spline parameter values to the PBD-X binary file.

To use PBDX2BSHAPE, run PBD-X using ILAT=2, then run PBDX2BSHAPE. The PBDOUT.IBG and PBDOUT.VCP files will be created. PBDX2BSHAPE will be updated as required for compatibility with new versions of PBD-X.

MTSET

Although the original version of MTSET is relatively easy to use, the controls for clustering grid points have proved insufficient. It is often necessary to cluster the grid points in way of the propulsor blades. The coupling with PBD-X and PBD-14 relies on a the flow grid being sufficiently dense to capture the velocities induced by the blades with a similar resolution as the blade lattice.

The original version of MTSET only allows for one clustered region; and in some instances, no clustered region is permitted. Furthermore, the clustering controls often do not allow as much clustering as the designer would like, or the ability to reduce the number of points in regions where they are not required.

Completely replacing MTSET with another grid generator and writing a program to convert from that format to the MTFLOW tdat format was considered. These modern grid generating programs have a graphical interface which allows the user to click on control points and adjust grid clustering. Additional control points can be easily added to cluster in other areas in contrast to the current MTSET with a command line interface and poor clustering control.

After some investigation, it was decided that while it was possible to replace MTSET, it would make it more difficult to deal with geometry variations in an automated fashion. For this

reason, it was decide to attempt to modify MTSET to allow more user control over the grid spacing.

MTSET was modified to use the spacing routines written by Stephen Neely and used in other NSWCCD software. These routines allow the user to choose from a variety of common spacings, such as uniform and cosine, and also allow the use of a powerful parabolic spacing specification. Furthermore, propulsor designers at NSWCCD are already familiar with the use of these routines.

The new version of MTSET checks for the presence of two files, `spc_elements`, and `spc_streamlines`. If found, each of these files overrides the some of the MTSET spacing routines. The spacing on the elements, such as the duct and hub, is controlled by `spc_elements`. The radial spacing, separating streamlines, is controlled by `spc_streamlines`.

MTSET expects elements to be defined counterclockwise so that the top is side one, the bottom is side two. `spc_elements` follows this convention. A sample `spc_elements` file for a case with just a hub, P4119, is shown in Table 1 and defined in Table 2.

MTSET defines streamline spacing based on an estimated stream function. A sample `spc_streamlines` file for a waterjet, AxWJ-2, is shown in Table 3 and defined in Table 4.

Table 1. Sample input file for grid spacing on elements, `spc_elements`.

```
nels
1
ispc1       ispc2
10          0
nw1
5
x1          dxdw1
0.0         1.0
0.2         0.2
0.55        0.2
0.75        1.0
1.0         2.0
```

Table 2. Definition of variables in `spc_elements`.

Variable	Definition	Recommended Values
`nels`	Number of elements for which spacing data is to be read	0 – ignore this file >0 – number of elements
For each element (`1 to nels`)		
`ispc1, ispc2`	Spacing flags for side one and side two for each element MTSET expects elements to be defined counterclockwise so that the top is side one, the bottom is side two Elements always have two sides, one may be a dummy	0 – uniform 1 – cosine 2 – half-cosine, close at start 3 – half-cosine, close at end 4 – double-cosine 5 – double cosine, close at start 6 – double cosine, close at end 10 – parabolic spacing
Only if `ispc1 = 10`		
`nw1`	Number of spacing pairs	Number of `x1, dw1` pairs to follow
`x1`	Relative distance	May be any range, will be normalized, typically 0-1
`dw1`	Relative spacing	May be any range, will be normalized, smaller for tighter spacing
Only if `ispc2 = 10`		
`nw2`	Number of spacing pairs	Number of `x2, dw2` pairs to follow
`x2`	Relative distance	May be any range, will be normalized, typically 0-1
`dw2`	Relative spacing	May be any range, will be normalized, smaller for tighter spacing

Table 3. Sample input file for grid spacing on elements, `spc_streamlines`.

```
nsls
1
ispc
10
nw
3
x           dxdw
0.0         0.3
0.5         1.0
1.0         0.3
```

Table 4. Definition of variables in `spc_streamlines`.

Variable	Definition	Recommended Values
`nsls`	Number of streamline groups, or regions, for which spacing data is to be read	0 – ignore this file >0 – number of streamline groups
For each streamline group (`1 to nsls`)		
`ispc`	Spacing flags for this region	0 – uniform 1 – cosine 2 – half-cosine, close at start 3 – half-cosine, close at end 4 – double-cosine 5 – double cosine, close at start 6 – double cosine, close at end 10 – parabolic spacing
Only if `ispc = 10`		
`nw`	Number of spacing pairs	Number of `x, dw` pairs to follow
`x`	Relative distance	May be any range, will be normalized, typically 0-1
`dw`	Relative spacing	May be any range, will be normalized, smaller for tighter spacing

Figures 31 and 32 compare grids generated for the AxWJ-2 and P4119, respectively, with the original and new versions of MTSET using the same number of points. With the new version, more grid points are clustered in way of the blades and fewer points are used far upstream and far downstream.

CONCLUSIONS

Comparative calculations show that PBD-X/MTFLOW reproduces PBD-14/MTFLOW predictions for open propellers when the two codes are executed with similar options. This result is encouraging. The two codes have different predictions for waterjet pumps, which is also encouraging because the PBD-14 predictions for waterjet pumps have been unsatisfactory to date.

Improvements have been made to PBD-X and MTSET to enhance capabilities and make the software easier to use.

FUTURE WORK

Collaborative work between Professor Kerwin and NSWCCD should continue. This is an effective way to improve communication and will ultimately result in better software for propulsor design.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Ki-Han Kim of ONR for funding this effort. Professor Justin Kerwin provided the current version of PBD-X and code still in development to support this project. Scott Black and Stephen Neely provided valuable suggestions throughout the project.

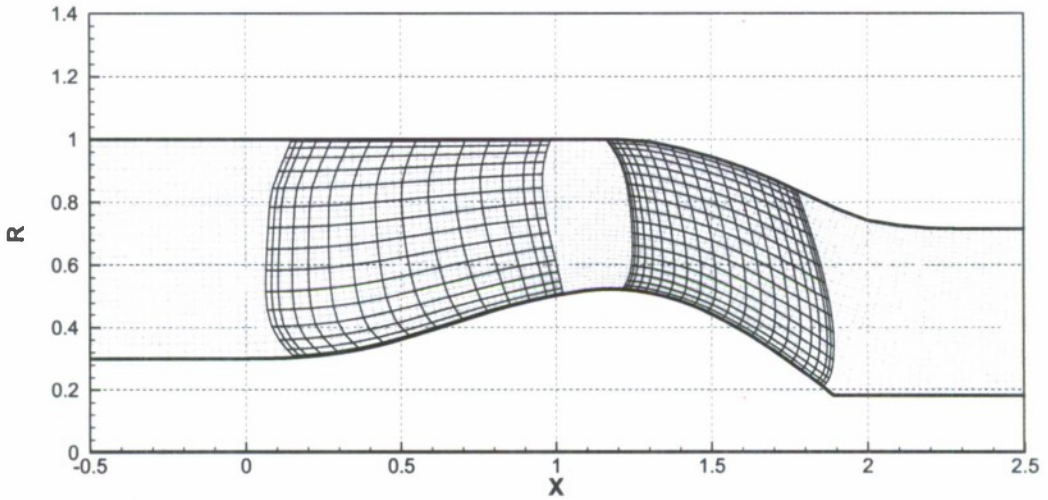

Figure 1. AxWJ-2: MTSOL mesh with blade swept areas.

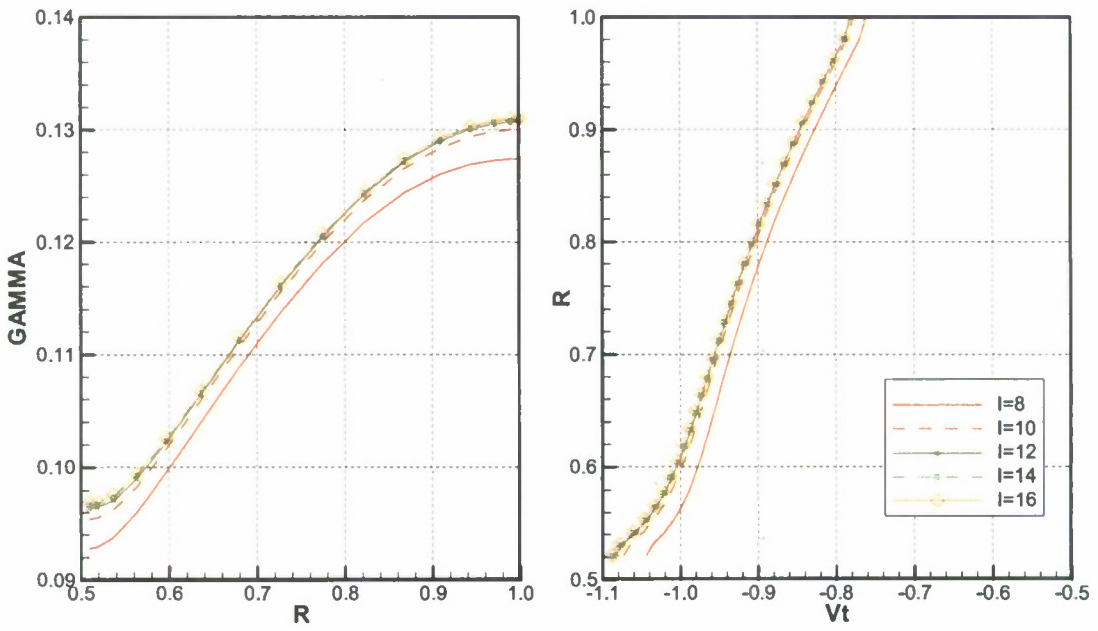

Figure 2. AxWJ-2: Effect of number of images, spanwise cosine spacing, MKEY=17.

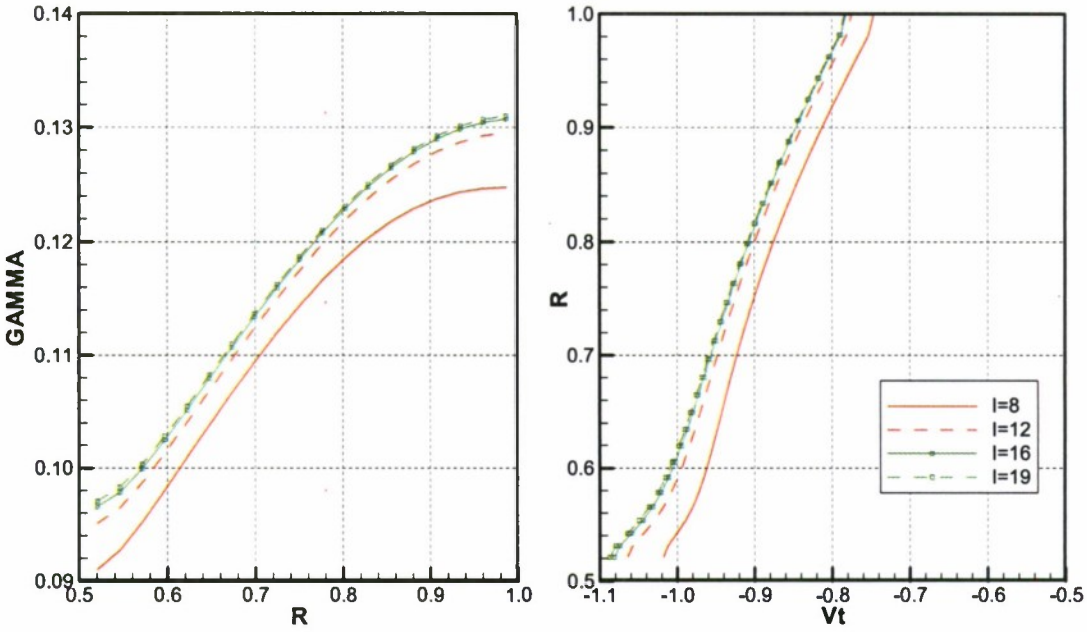

Figure 3. AxWJ-2: Effect of number of images, uniform spanwise spacing, MKEY=20.

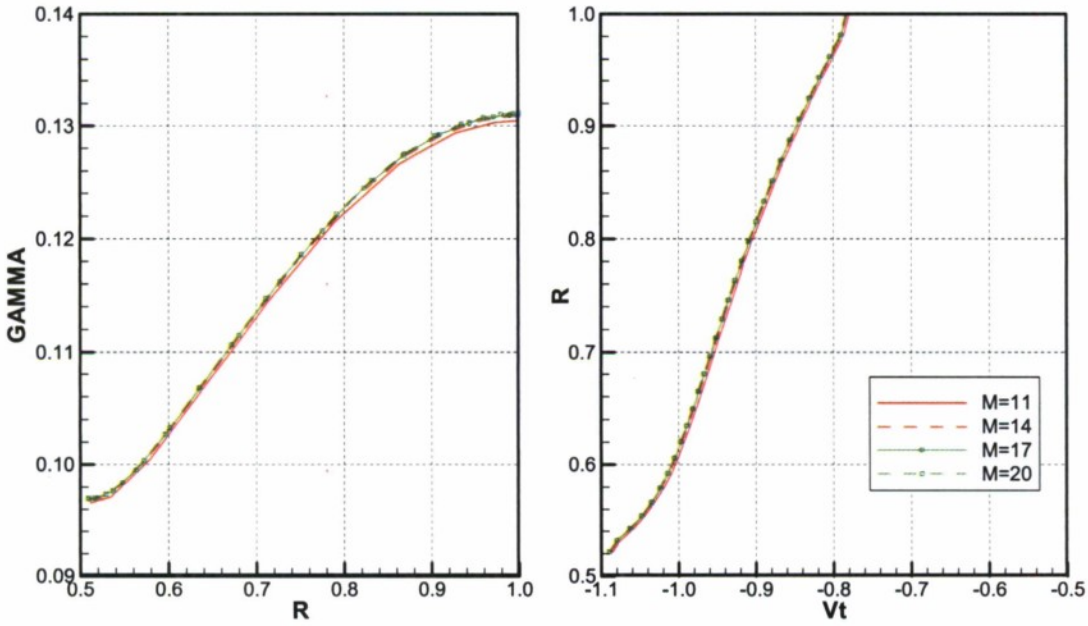

Figure 4. AxWJ-2: Effect of MKEY, spanwise cosine spacing, number of images set to MKEY-1. NKEY similar to MKEY.

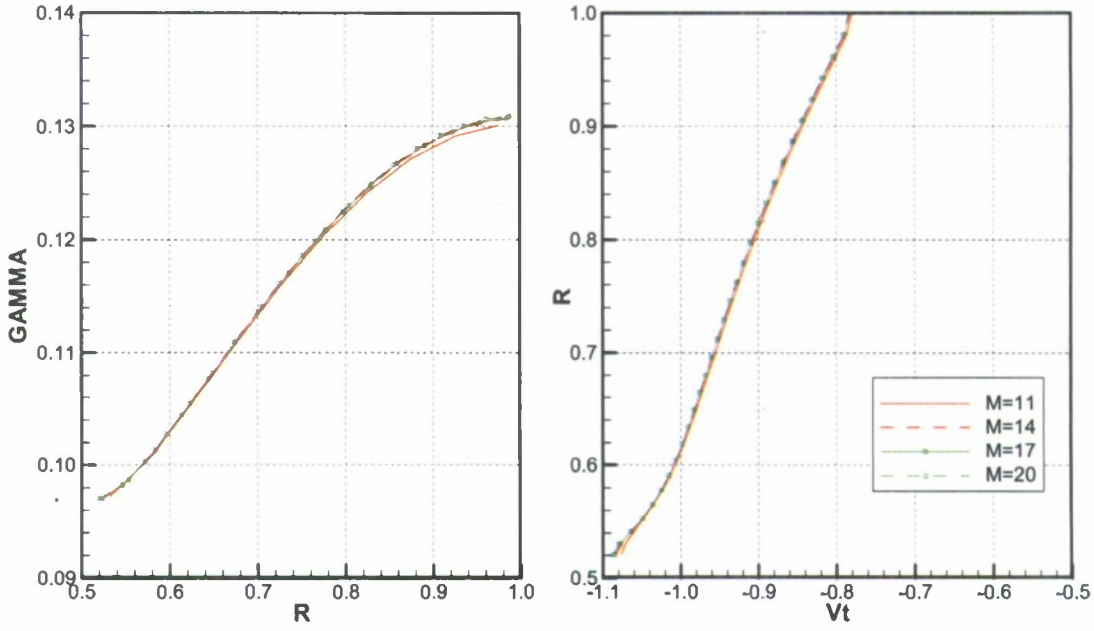

Figure 5. AxWJ-2: Effect of MKEY, uniform spanwise spacing, number of images set to MKEY-1. NKEY similar to MKEY.

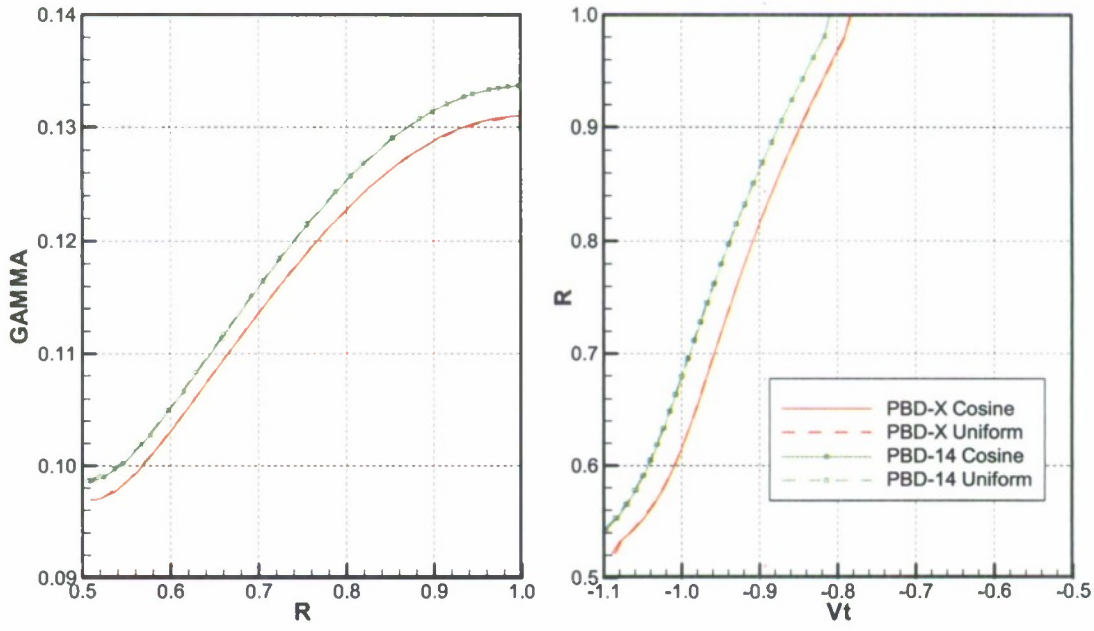

Figure 6. AxWJ-2: Comparison of PBD-X and PBD-14, MKEY=17, 16 images.

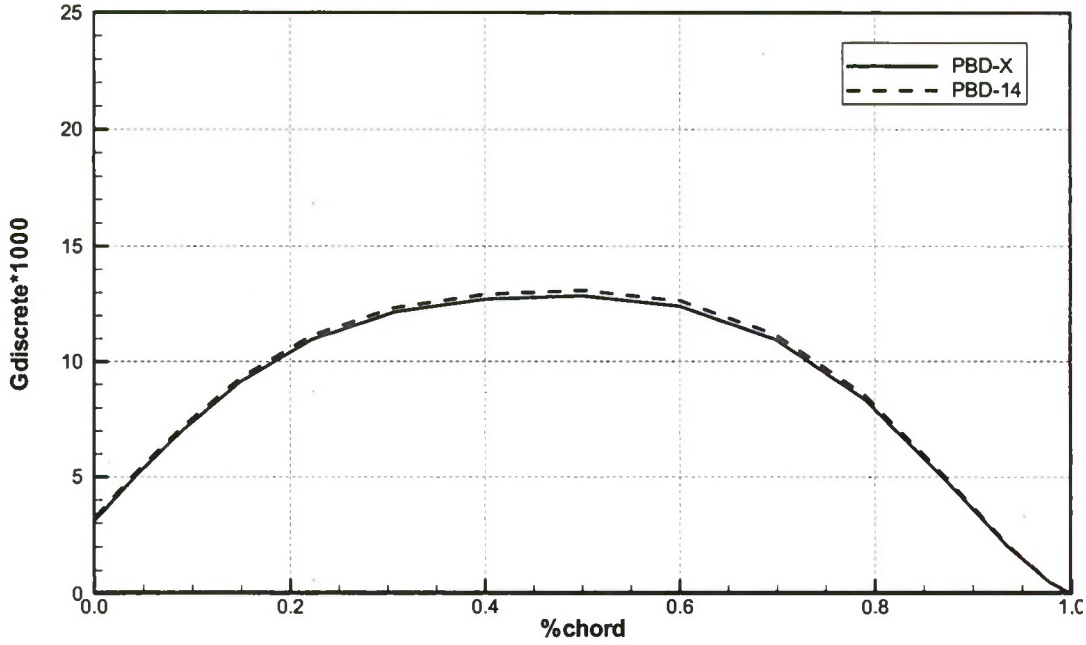

Figure 7. AxWJ-2: Comparison of PBD-X and PBD-14 chordwise loading, MKEY=17, 16 images.

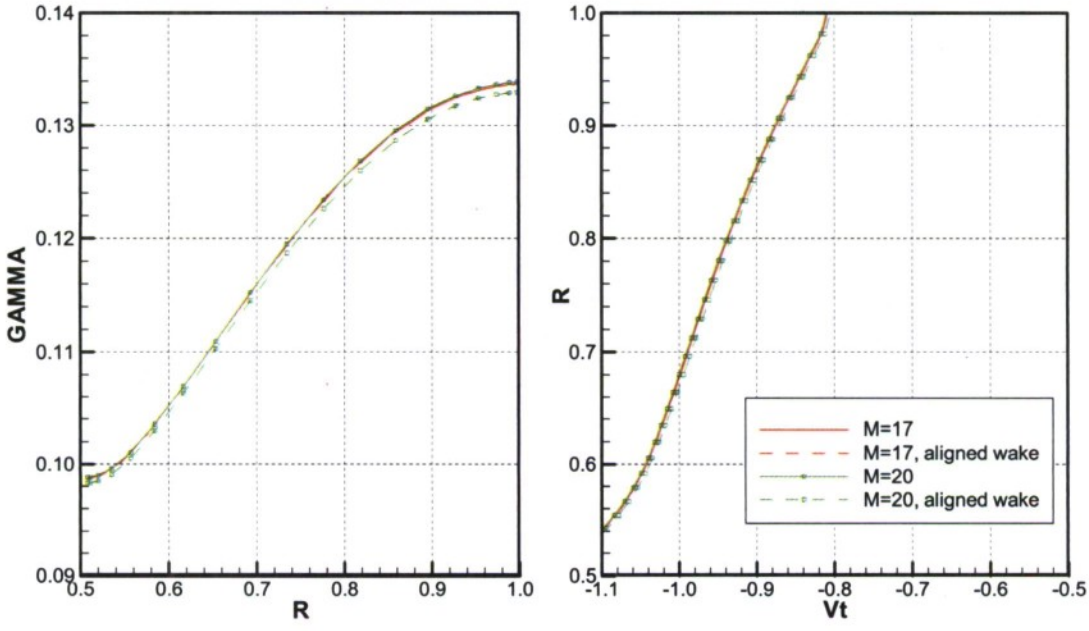

Figure 8. AxWJ-2: Effect of wake alignment on PBD-14, cosine spanwise spacing.
The two cases with wake alignment are identical.

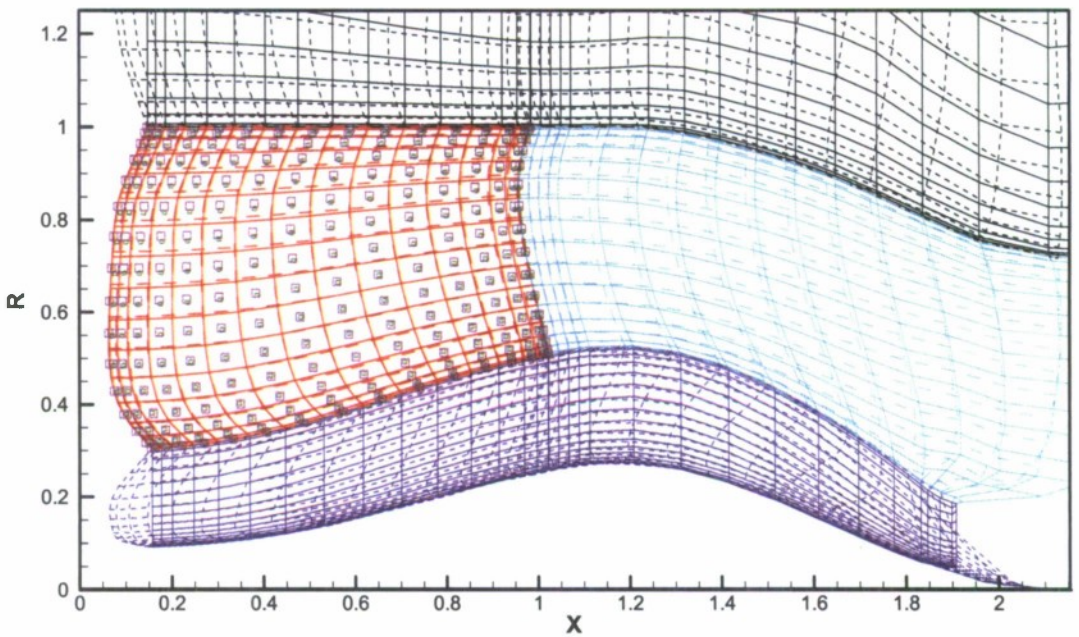

Figure 9. AxWJ-2: Two-dimensional comparison of lattices and control points. Solid lines are PBD-X; dashed lines are PBD-14.

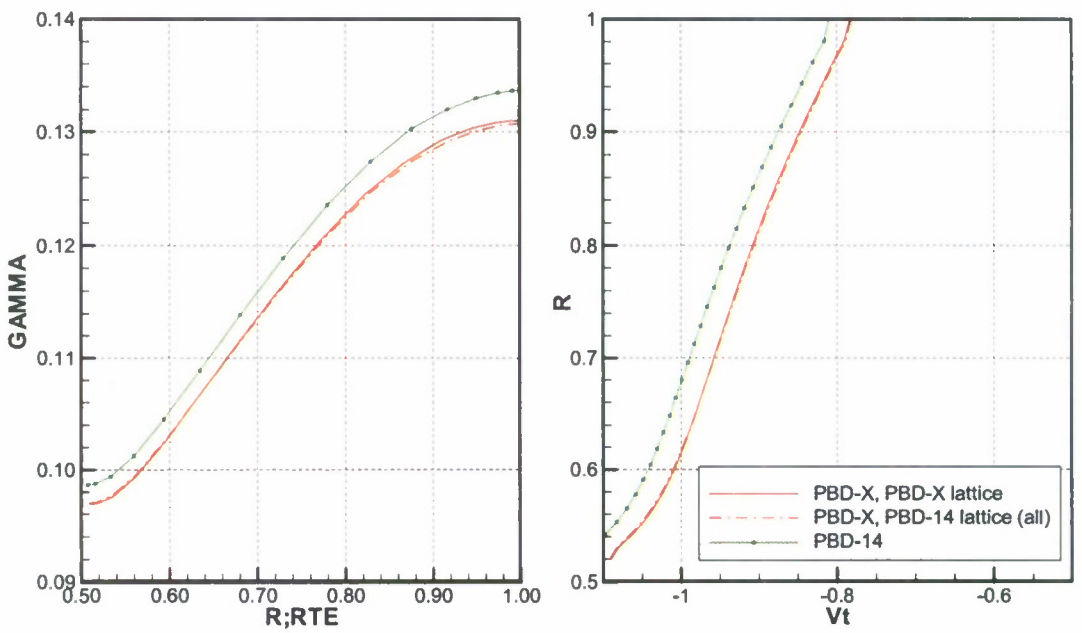

Figure 10. AxWJ-2: Effect of using PBD-14 lattices in PBD-X.

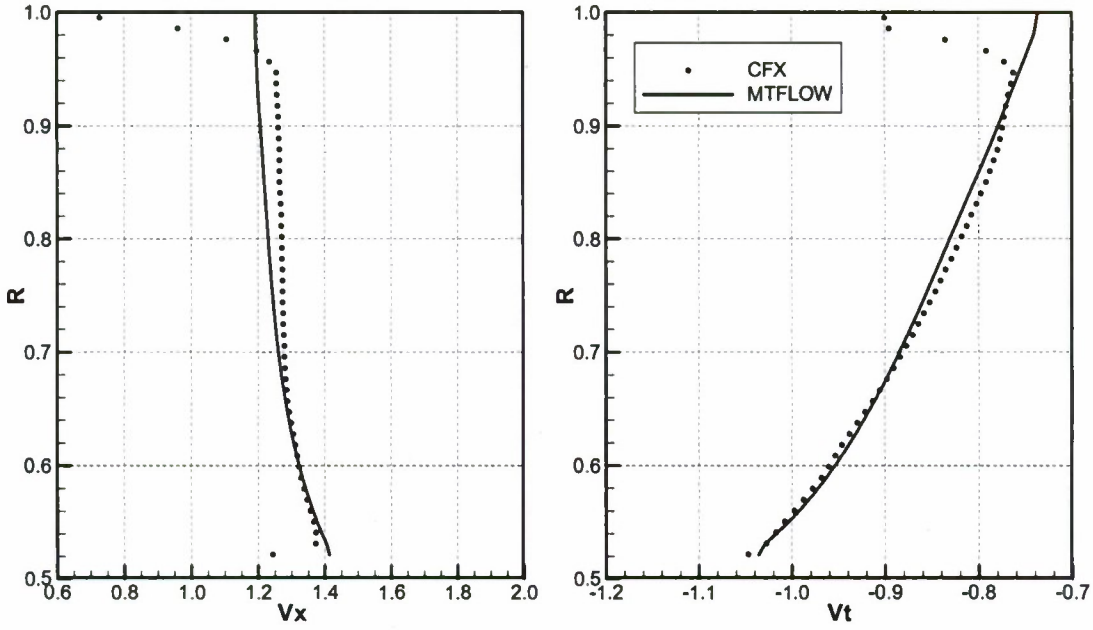

Figure 11. AxWJ-2 stator: Comparison of CFX and MTFLOW inflow.

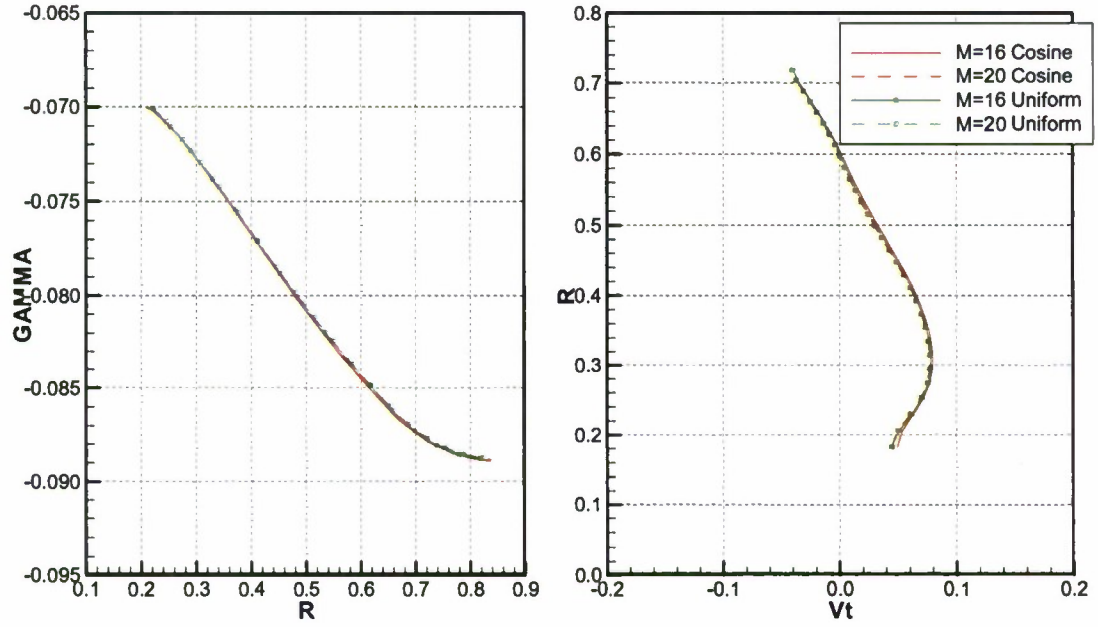

Figure 12. AxWJ-2 stator: Convergence of MKEY for uniform and cosine spanwise spacing.

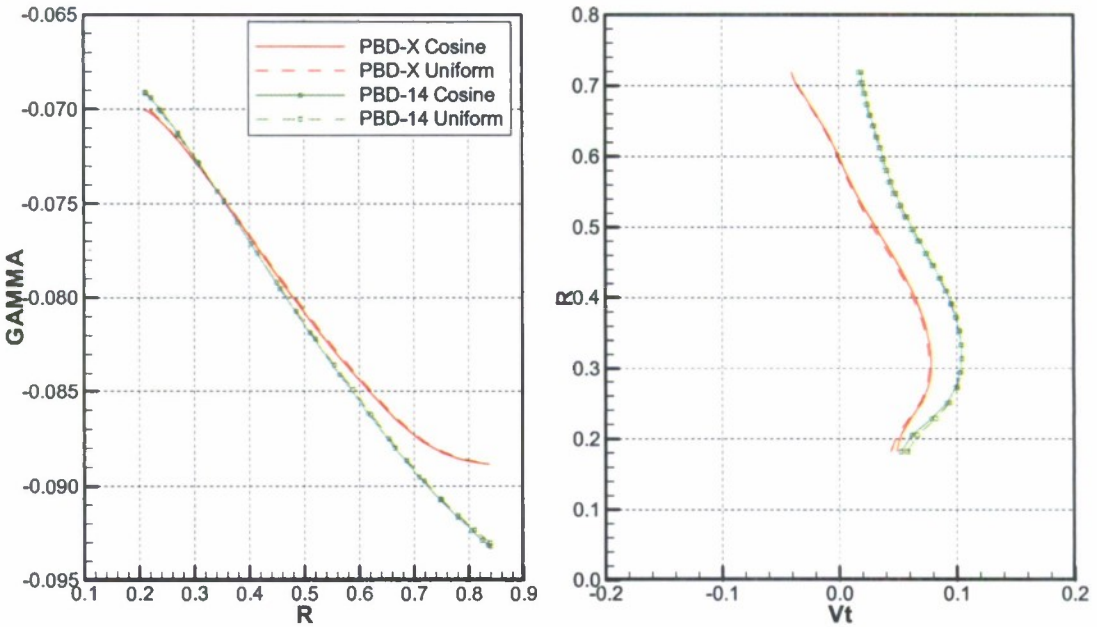

Figure 13. AxWJ-2 stator: Comparison of PBD-X and PBD-14, MKEY=20, 19 images.

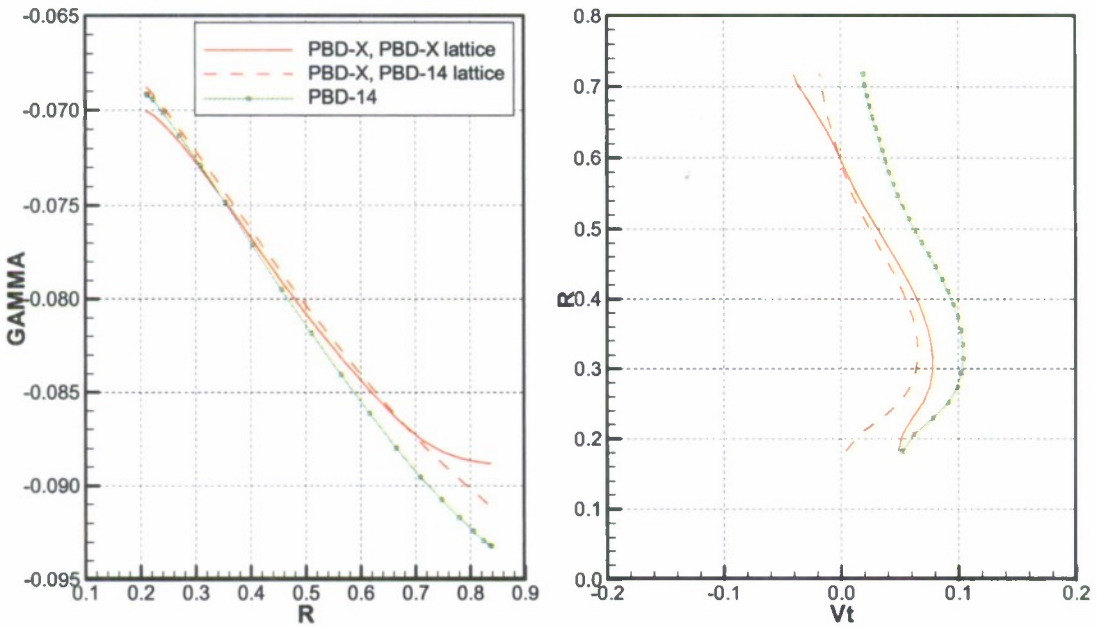

Figure 14. AxWJ-2 stator: Comparison of PBD-X and PBD-14, MKEY=20, 19 images, cosine spacing.

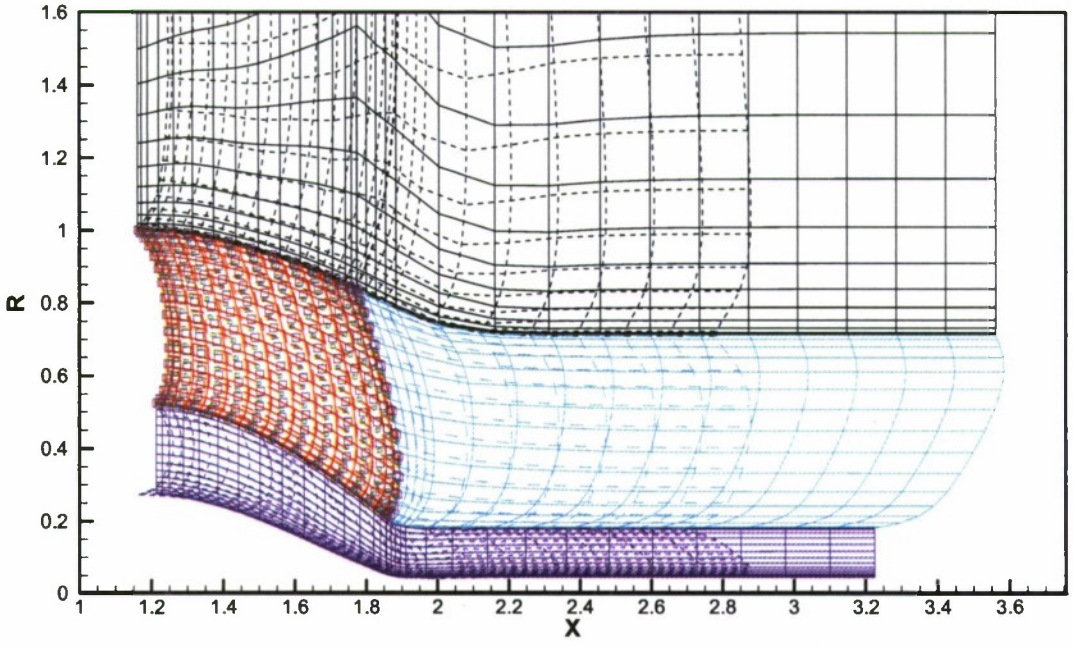

Figure 15. AxWJ-2 stator: Two-dimensional comparison of lattices and control points. Solid lines are PBD-X; dashed lines are PBD-14.

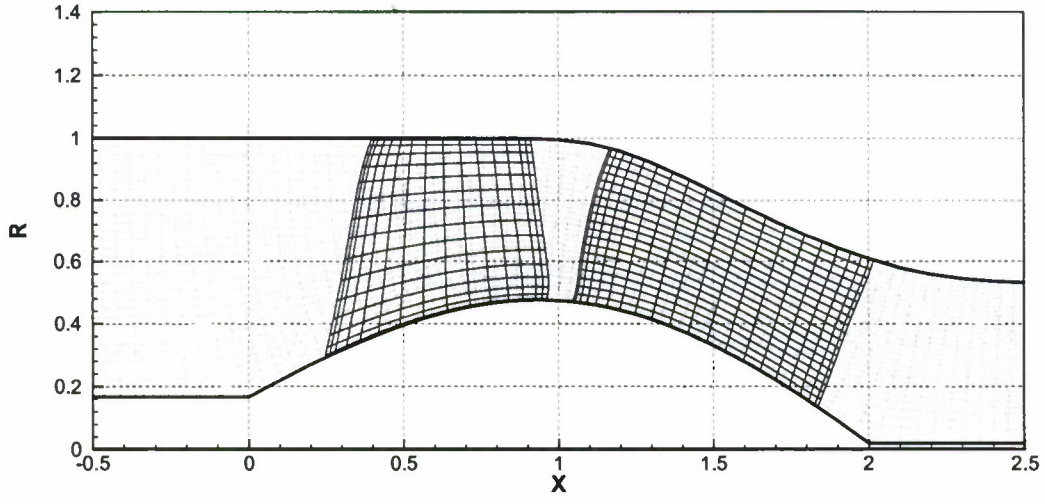

Figure 16. AxWJ-1: MTSOL mesh with blade swept areas.

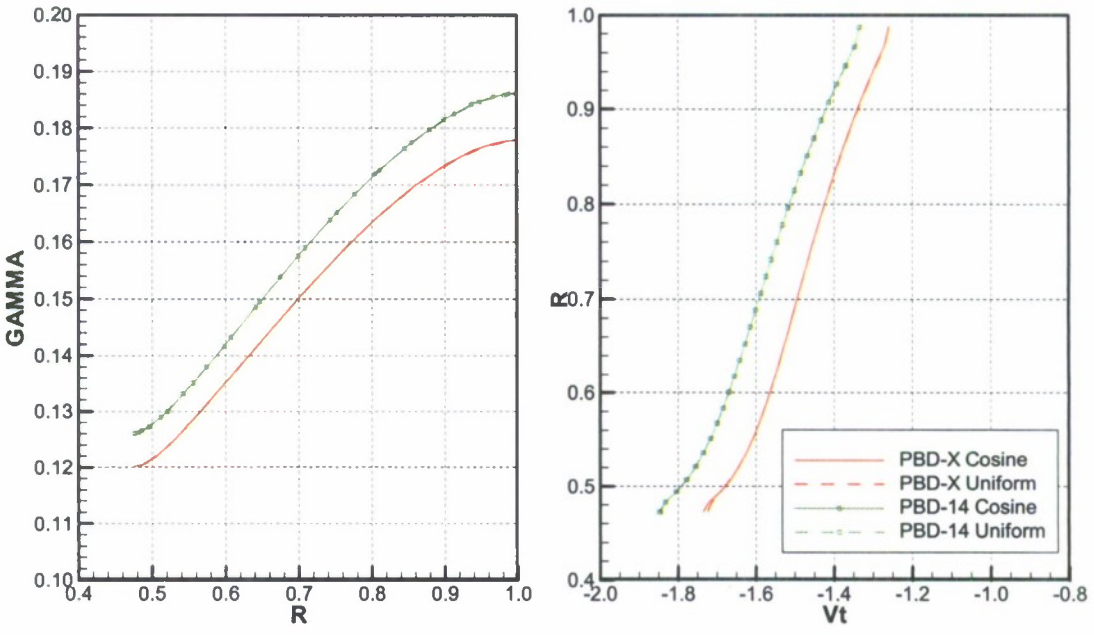

Figure 17. AxWJ-1: Comparison of PBD-X and PBD-14, MKEY=17, 16 images.

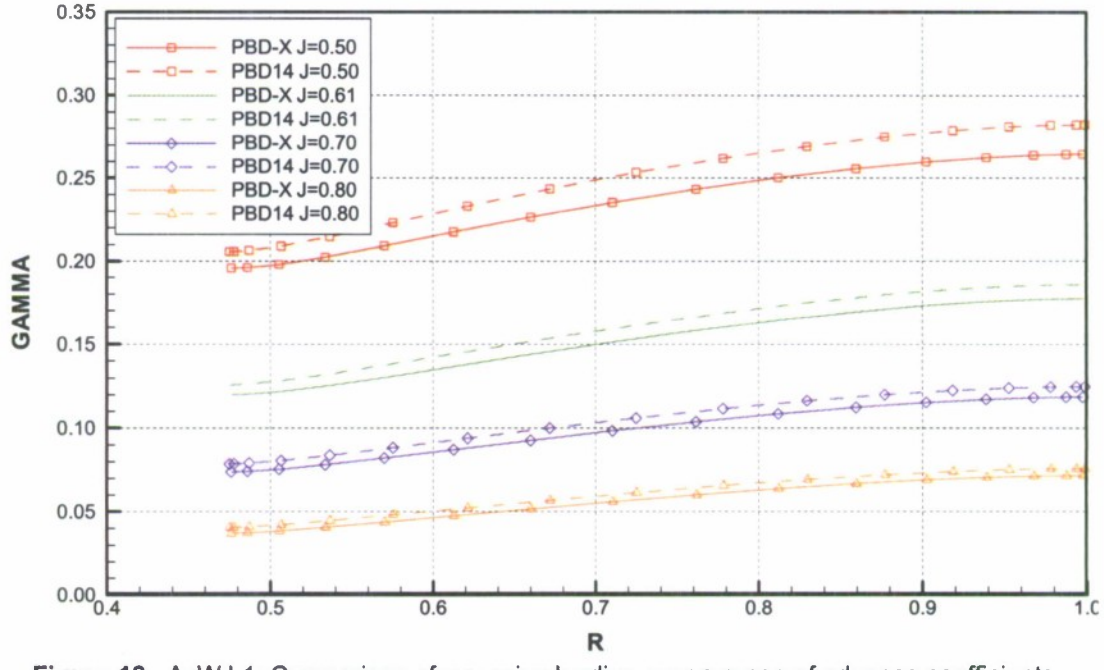

Figure 18. AxWJ-1: Comparison of spanwise loading over a range of advance coefficients, MKEY=17.

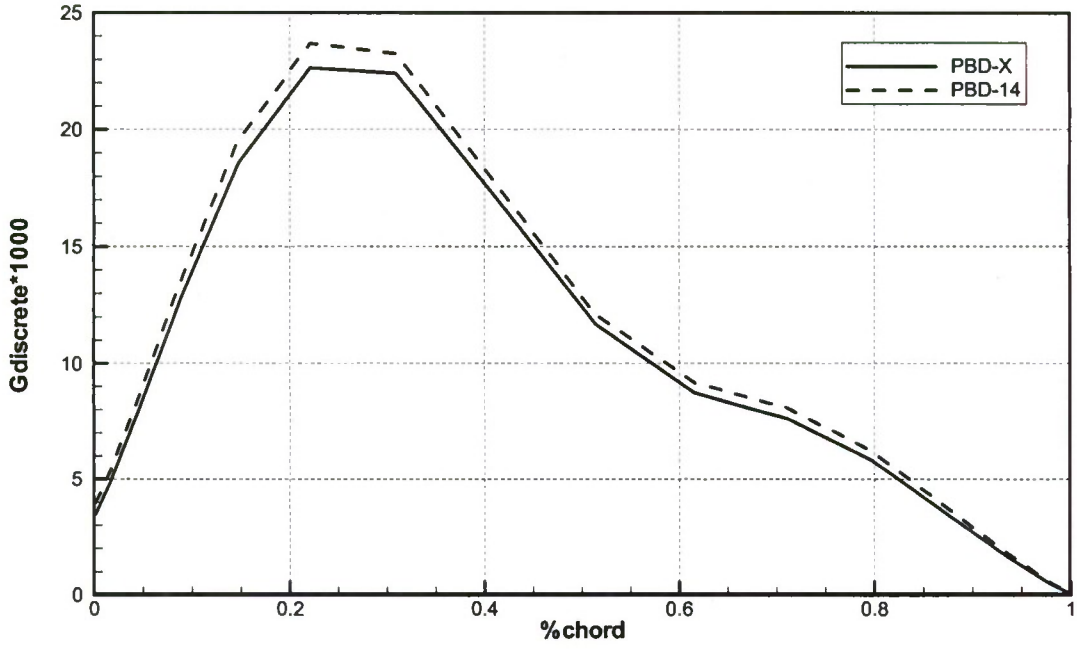

Figure 19. AxWJ-1: Comparison of chordwise loading at midspan, design advance coefficient.

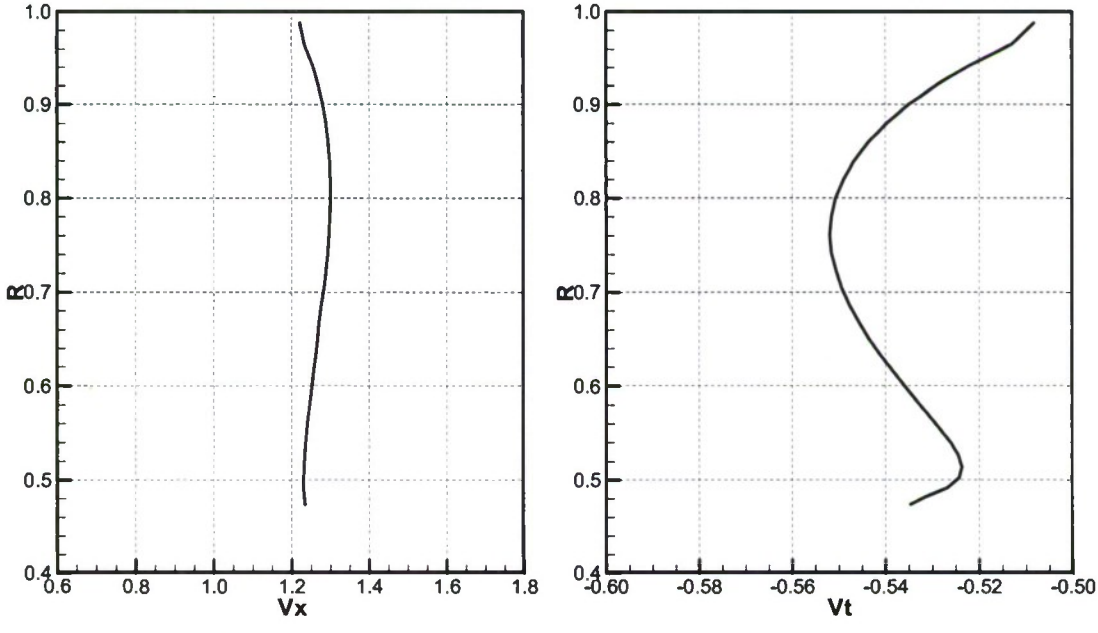

Figure 20. AxWJ-1 stator: Inflow velocity distribution, rotor advance coefficient of 0.80.

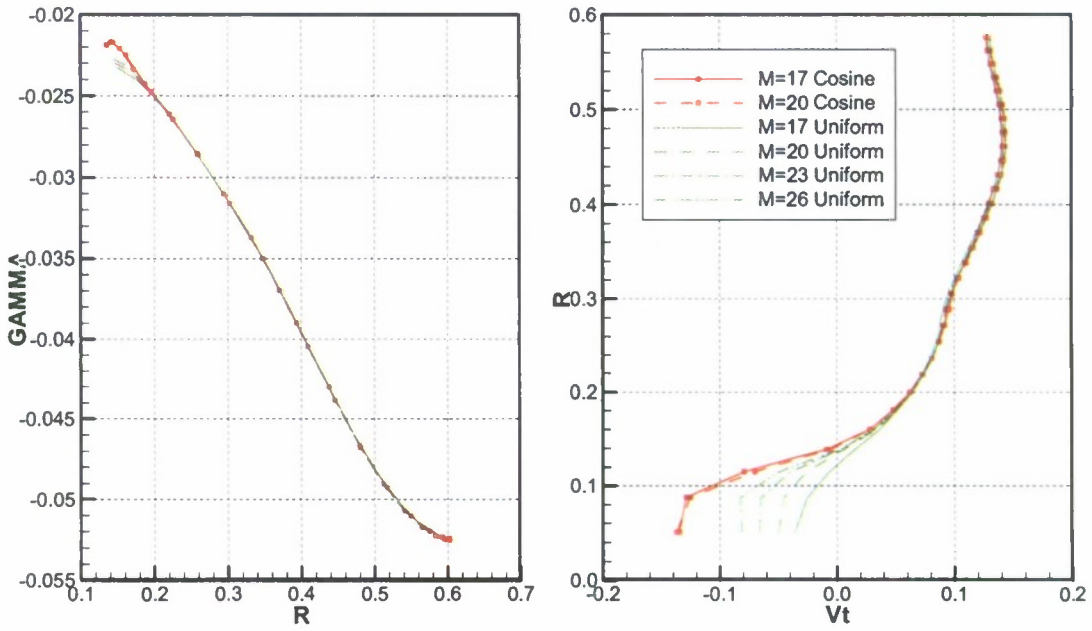

Figure 21. AxWJ-1 stator: Convergence of MKEY.

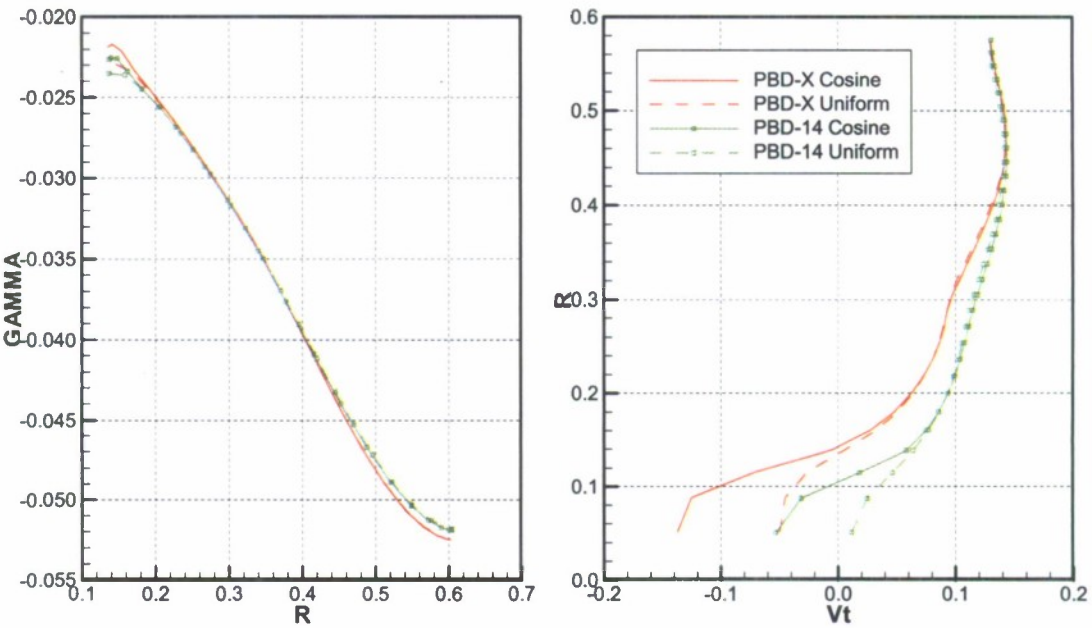

Figure 22. AxWJ-1 stator: Comparison of PBD-X and PBD-14, MKEY=20, 19 images.

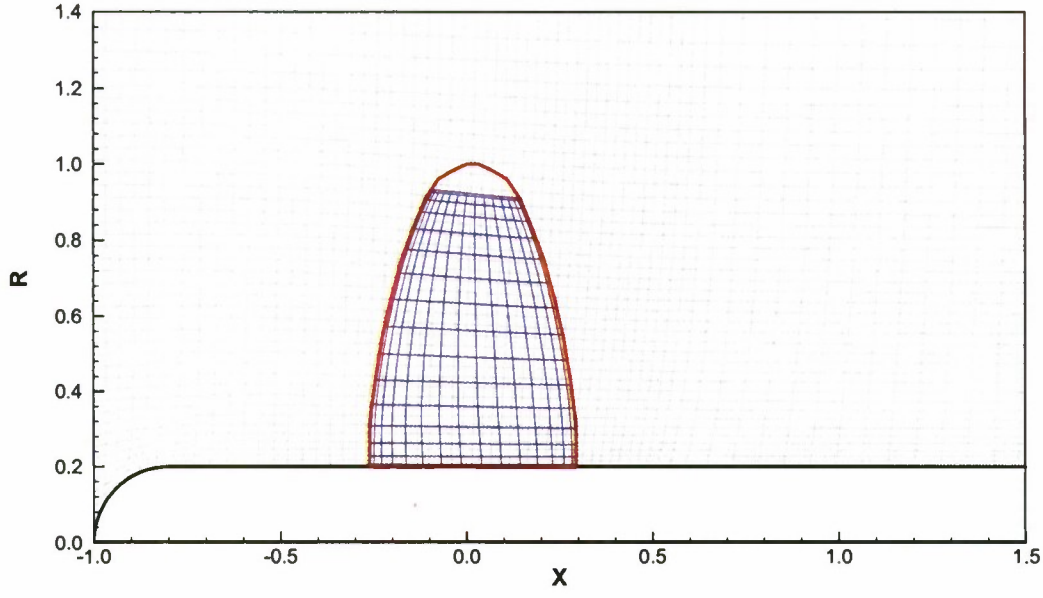

Figure 23. P4119: Cropped tip due to lattice generation routine.

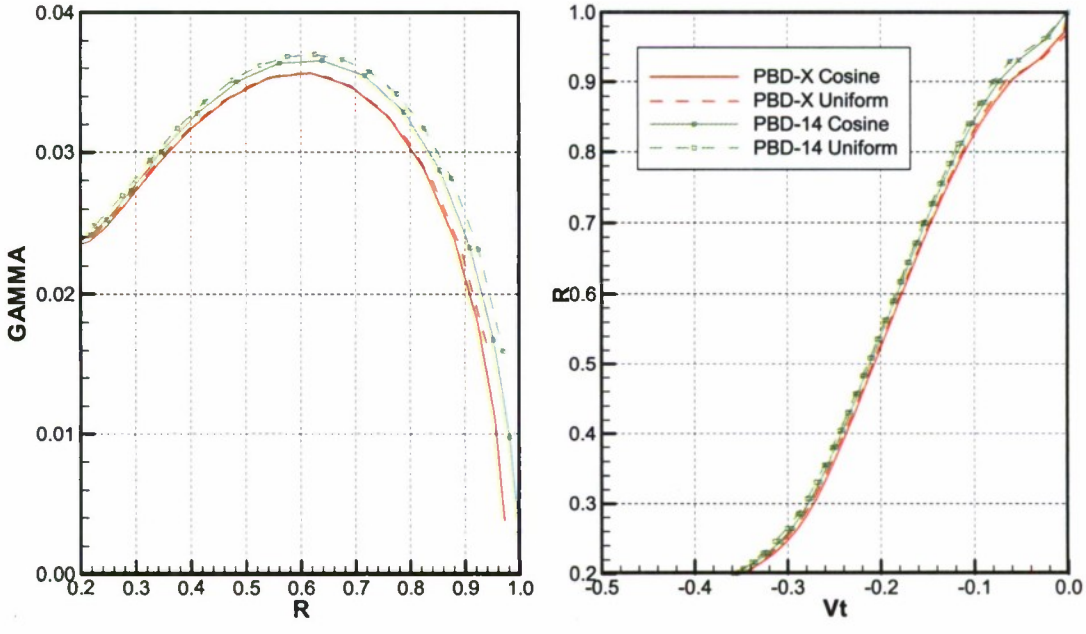

Figure 24. P4119: Comparison of PBD-X and PBD-14 results.

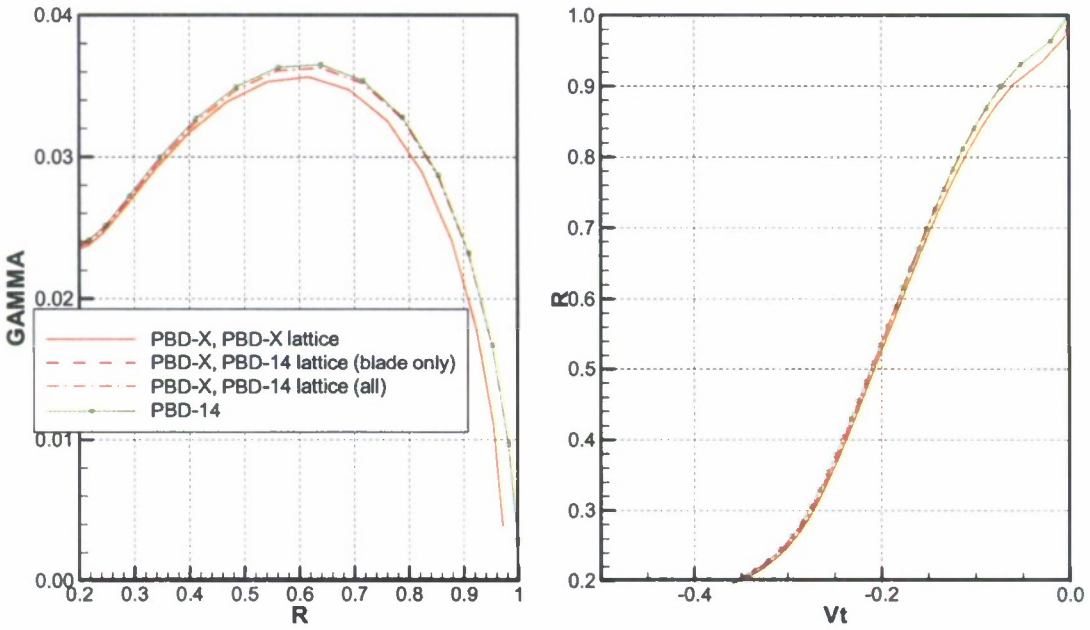

Figure 25. P4119: Effect of using PBD-14 lattice in PBD-X.

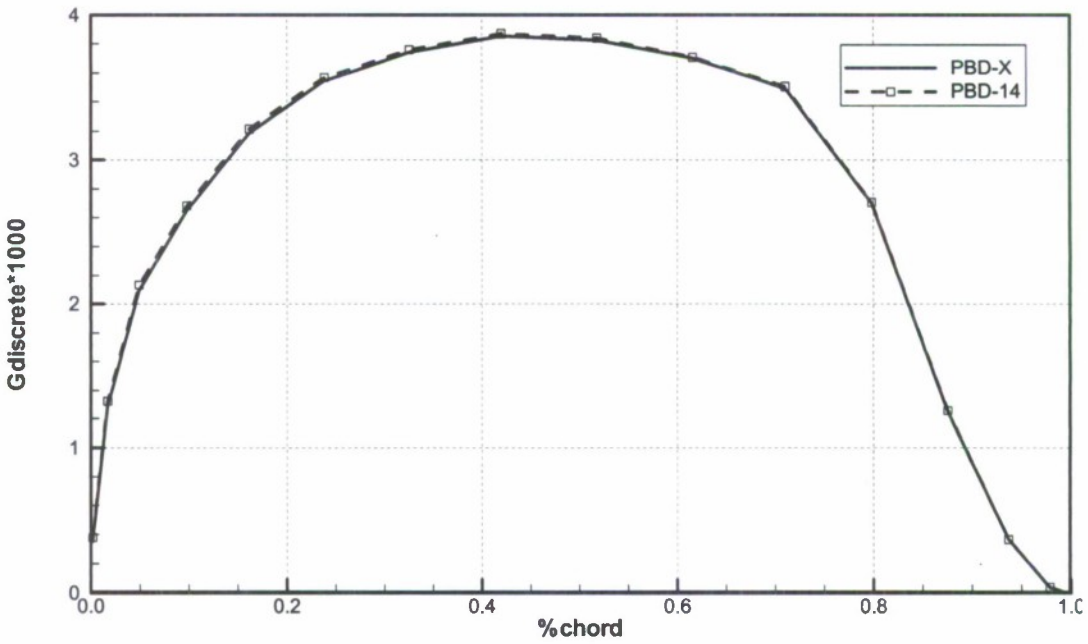

Figure 26. P4119: Chordwise circulation distribution at midspan.

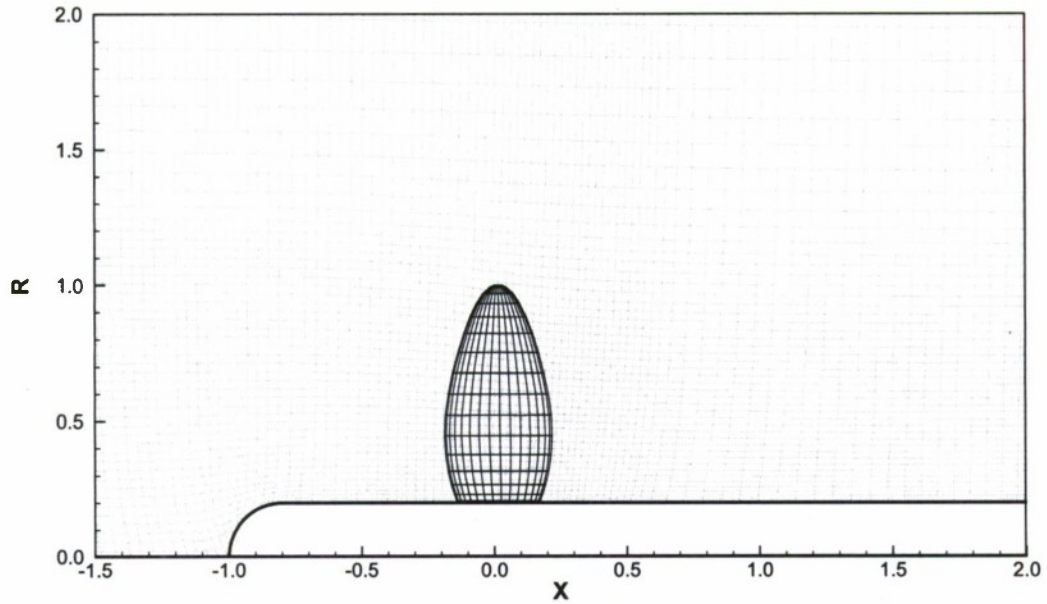

Figure 27. P4381: MTSET grid and PBD-14 lattice.

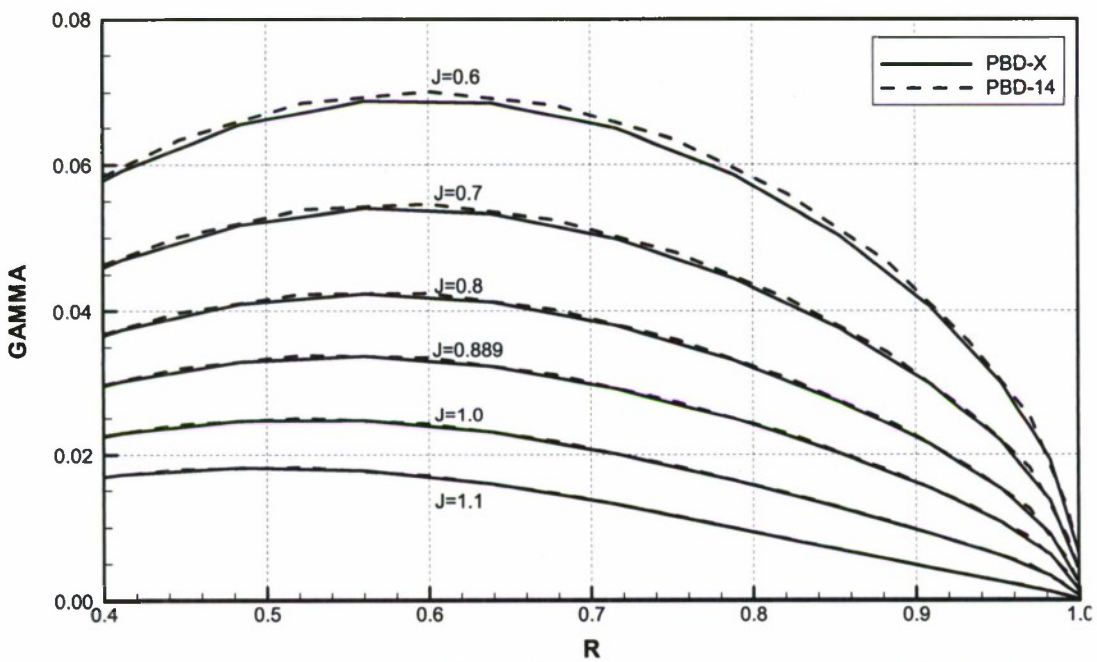

Figure 28. P4381: Spanwise circulation comparison over a range of advance coefficients. PBD-14 lattice used in PBD-X.

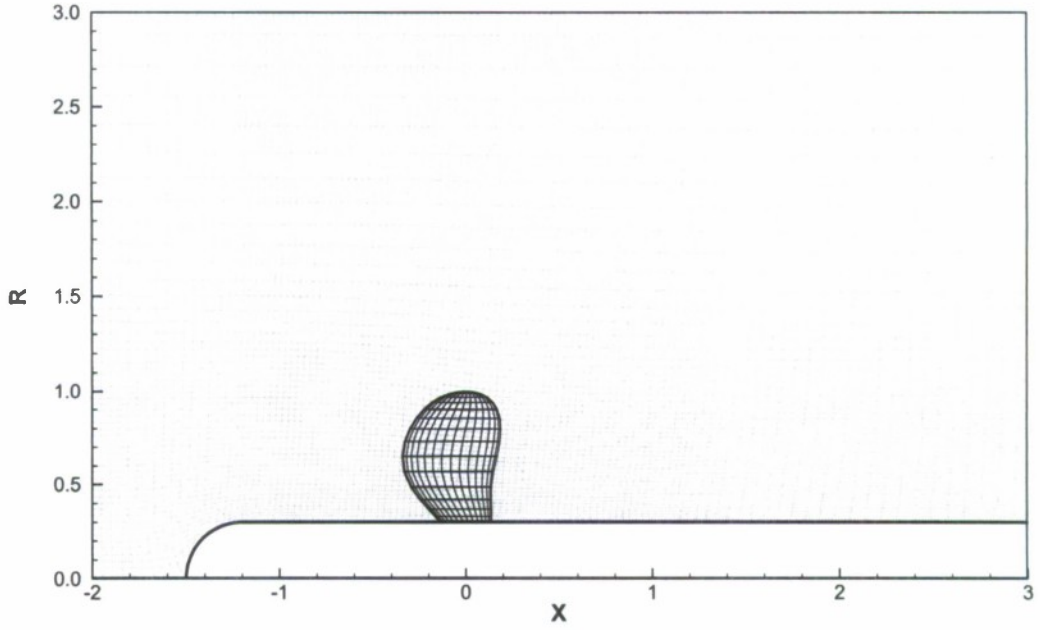

Figure 29. P4990: MTSET grid and PBD-14 lattice.

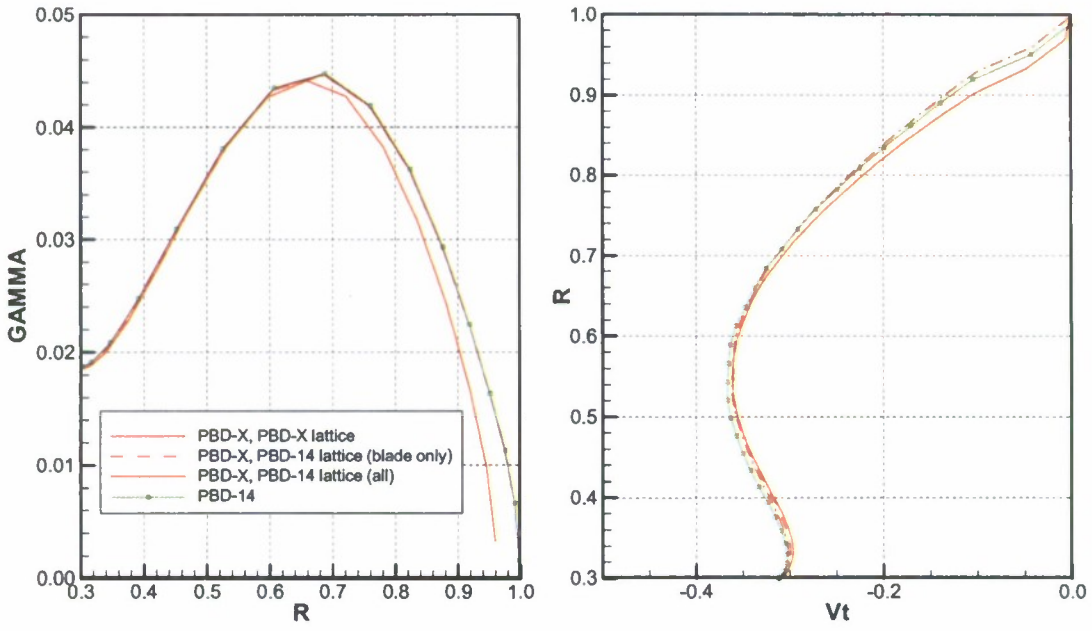

Figure 30. P4990: Comparison of PBD-14 and PBD-X with various lattices, MKEY=17.

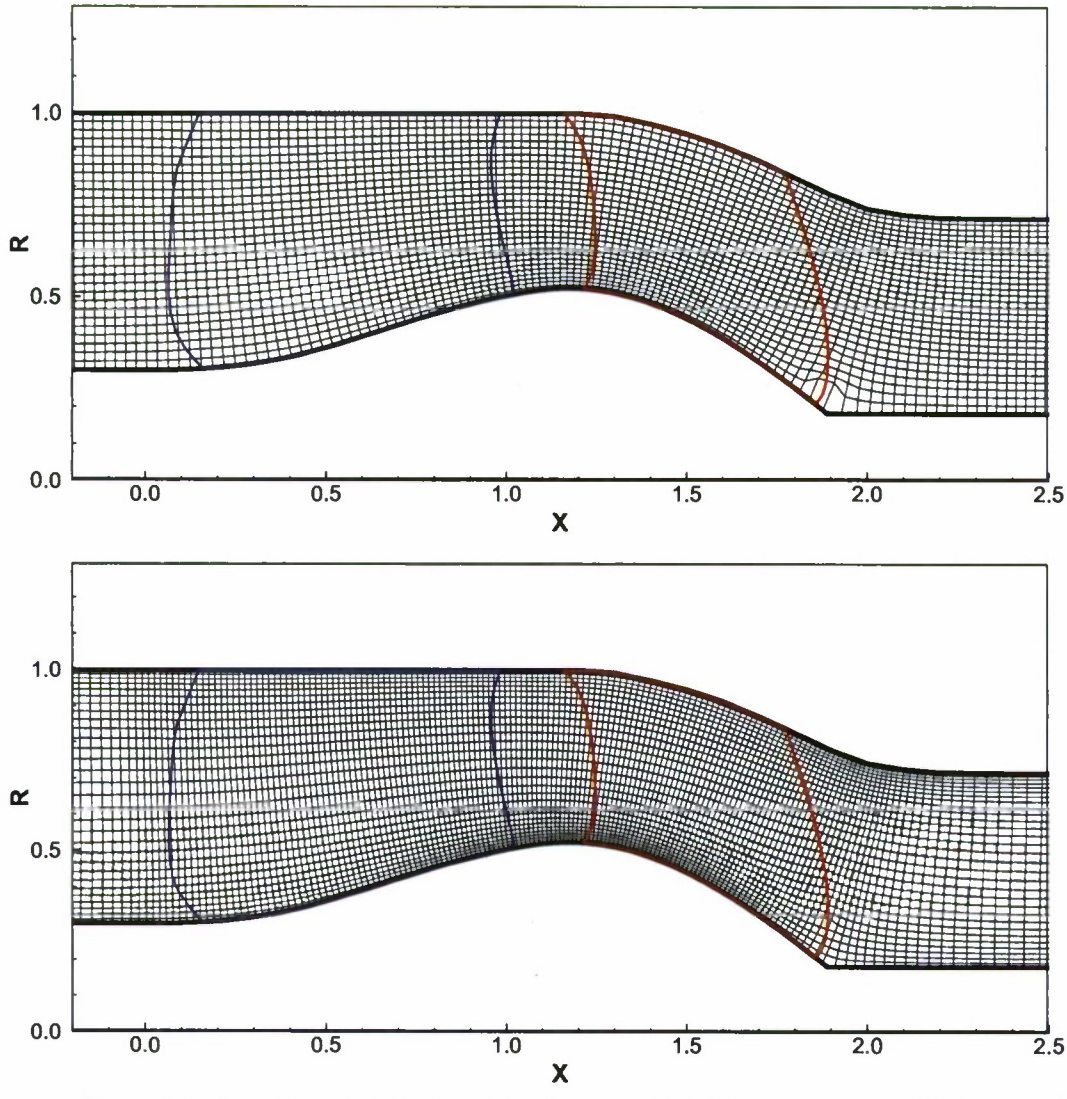

Figure 31. Comparison of grids generated for AxWJ-2 with old and new MTSET.

Top: original method; bottom: new method.

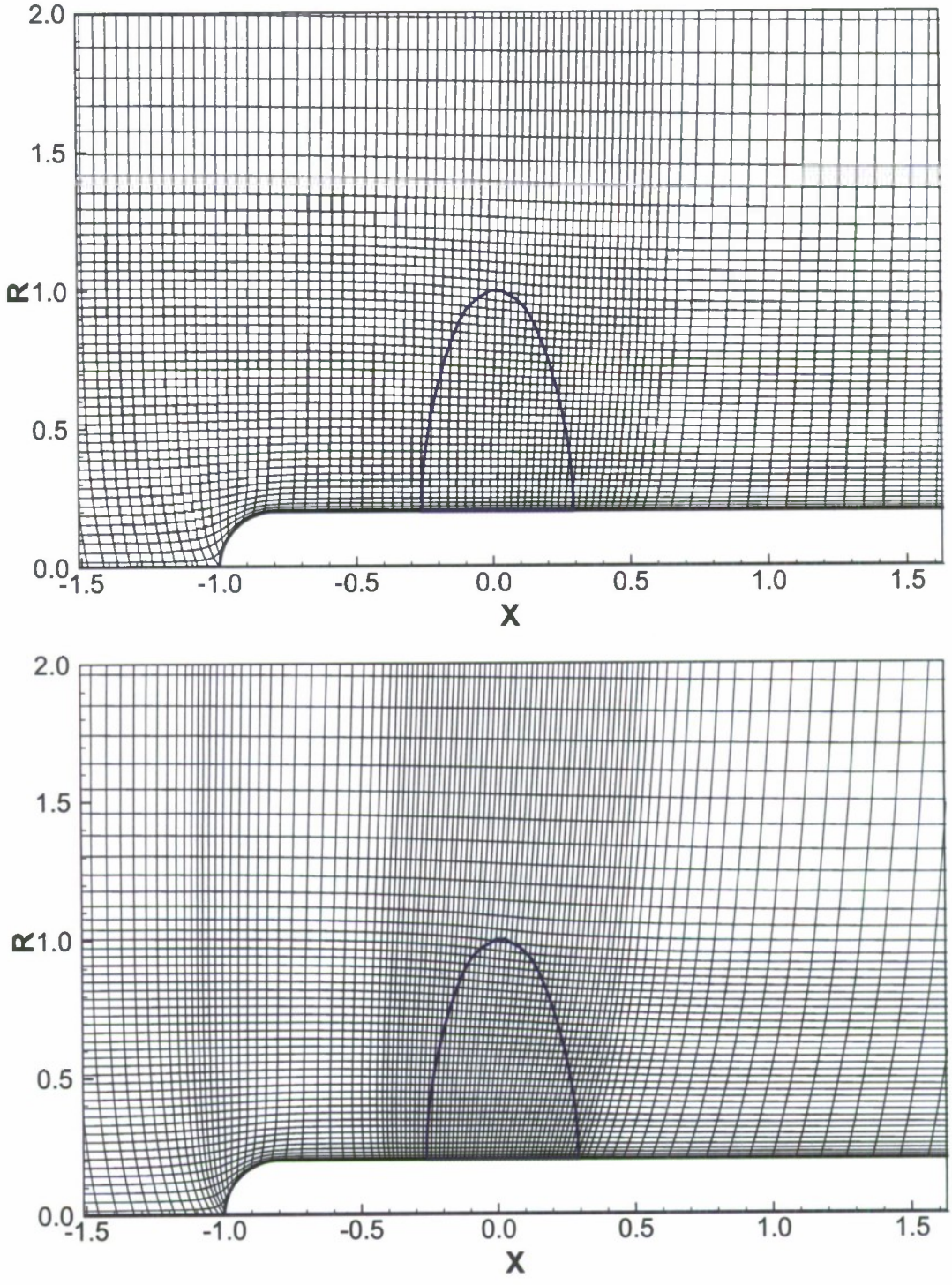

Figure 32. Comparison of grids generated for P4119 with old and new MTSET. Top: original method; bottom: new method.

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REFERENCES

1. Kerwin, J. E., et. al., "A Coupled Viscous/Potential Flow Design Method for Wake-Adapted Multi-Stage, Ducted Propulsors Using Generalized Geometry," SNAME *Transactions*, 1994.

2. Kerwin, J.E., Michael, T.J., and Neely, S.K., "Improved Algorithms for the Design/Analysis of Multi-Component Complex Propulsors," SNAME Propellers and Shafting Symposium, September 2006.

3. Drela, M. and Giles, M., "Conservative Streamtube Solution of Steady-State Euler Equations," Technical Report CFDL-TR-83-6, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, November 1983.

4. Renick, D.H., "An Analysis Procedure for Advanced Propulsor Design," Masters Thesis, Ocean Engineering Department, Massachusetts Institute of Technology, May 1999.

5. Michael, T.J., S.D. Schroeder, and A.J. Becnel, "Design of the ONR AxWJ-2 Axial Flow Water Jet Pump," NSWCCD Report NSWCCD-50-TR-2008/066, November 2008.

6. Wu, H., et. al., "Cavitation in the Tip Region of the Rotor Blades within a Waterjet Pump," Proceedings of FEDSM2008, Fluids Engineering Conference 2008.

7. Jessup, S.D., "An Experimental Investigation of Viscous Aspects of Propeller Blade Flow," Ph.D. Dissertation, The Catholic University of America, 1989.

8. Chesnakas, C.J., *et. al.*, "Performance of Propeller 4381 in Crashback," NSWCCD Report NSWCCD-50-TR-2004/010, December 2004.

9. Jessup, S.D., K.D. Remmers, and W.G. Berberich, "Comparative Cavitation Performance Evaluation of a Naval Ship Propeller," *Proceedings*, ASME Cavitation Inception, New Orleans, Louisiana, 1993.

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