Inclusion of vane geometry in gust-cascade interaction prediction via a BVI method

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A method for increasing the geometric fidelity of a fan-stage, broadband, interaction noise model is investigated. Such an increase in fidelity is desired to eliminate the current dependence on stagger selection that exists when vanes are modeled as flat plates in the low-order method. The blade vortex interaction (BVI) technique has been used to include geometry effects in broadband computations previously and as such it is considered for this application. The connection between the BVI model and the gust model is described. A BVI prediction method for a single airfoil is presented. The single airfoil framework is extended to model BVI for a cascade using a transformation that maps the cascade into a single body. Restrictions that arise due to the transformation are discussed. The unsteady cascade response is computed for various airfoil geometries and cascade gap-to-chord ratios. While the method has some positive attributes, it is determined that the restrictions are too great to enable it to be used for realistic turbomachinery geometries and flow conditions.

I. Introduction

In the hydroacoustics community, the blade vortex interaction (BVI) model has been used as a basis for propeller broadband acoustic calculations[1,2]. Success has been achieved due to the low Mach number and large blade spacing present in the hydroacoustic application which allows the system of blades to be approximated by a single airfoil. Of particular importance, has bene the ability to utilize this model to assess the influence of propeller section geometry (e.g. thickness, camber) on the broadband noise. The connection between the BVI method and the gust interaction problem which forms a basis for the hydroacoustic calculations was originally presented by Widnall[3]. Subsequently, studies by Martinez[4] which used an analytical method to perform the BVI analysis and Grace[5] which used a boundary element method for the BVI analysis helped explain experimental findings by the Navy that showed that airfoil thickness decreased the broadband noise especially at higher frequencies[6]. The panel method based computations of Devenport[1] and Lysak[2] furthered the use of the BVI model as a method for addressing broadband noise in hydroacoustic systems.

As discussed previously, low-order modeling of broadband interaction noise downstream of a fan stage in a turbofan engine could benefit from the inclusion of vane geometry effects[7]. Currently, the low-order methods rely on a modeling of the fan exit guide vane (FEGV) as a flat vane. While excellent trend prediction and prediction of the the actual noise spectrum are obtained, inclusion of vane geometry would greatly improve the method in terms of eliminating an ad hoc choice of flat vane stagger required in the method. However, the hydroacoustic BVI approach cannot be immediately applied to turbomachinery applications because of the higher Mach numbers of interest and the close spacing of the vanes. Indeed it has been shown

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that cascade response must be utilized in the low-order method as opposed to single airfoil response when considering realistic vane counts[8].

Boundary element based methods which are related to panel methods but are much more broadly applicable have been used in the subsonic and transonic flow regimes to model unsteady aerodynamics. Thus, the computational method for BVI at the higher Mach numbers required for turbomachinery applications exists. What must be explored is the inclusion of the close vane spacing.

Preliminary thoughts on extending the BVI method to a comparable cascade model were first discussed in[7]. In this paper, the results from further investigations on this topic are described. A basic computational approach for the BVI problem is first described and applied to the response of a single airfoil. Then, a method for performing a cascade BVI computation based on a cascade transformation developed by Bhimarasetty and Govardhan[9] and previously implemented by Grace et al[7] is presented. Results related to the impact of vane geometry on the BVI response are then discussed. Finally, an overall recommendation concerning this method is presented.

II. Computational method and model

a. BVI calculation for a Single Airfoil

To simulate the passage of a vortex over a single airfoil, a 2D linear vortex panel method, as described in Kuethe and Chow[10], has been extended. The simulation is carried out in the time domain. A vortex is imposed upstream of the airfoil. The interaction between the vortex and the airfoil results in a change of lift. In order to conserve circulation, a vortex is then released in the wake. The imposed vortex and the wake vortex are then convected by the local flow creating another change in lift. The vortex path can be determined in several ways. Normally, one calculates the local flow velocity from the panel contributions at each time step and moves the vortex accordingly. If the strength of the imposed vortex is small enough, the vortex always follows a steady-flow streamline[5]. This result can be utilized to speed up the calculations by determining the vortex path a priori by defining the streamline along which it will convect. In the unsteady analysis, a wake is generated due to the interaction of the vortex and the airfoil. The wake is modeled using point vortices which physically should be convected by the local mean flow. Again though, a fixed wake model can be used to speed up the calculations. The wake path can be determined a priori based on the stagnation streamline behind the airfoil in the steady flow case.

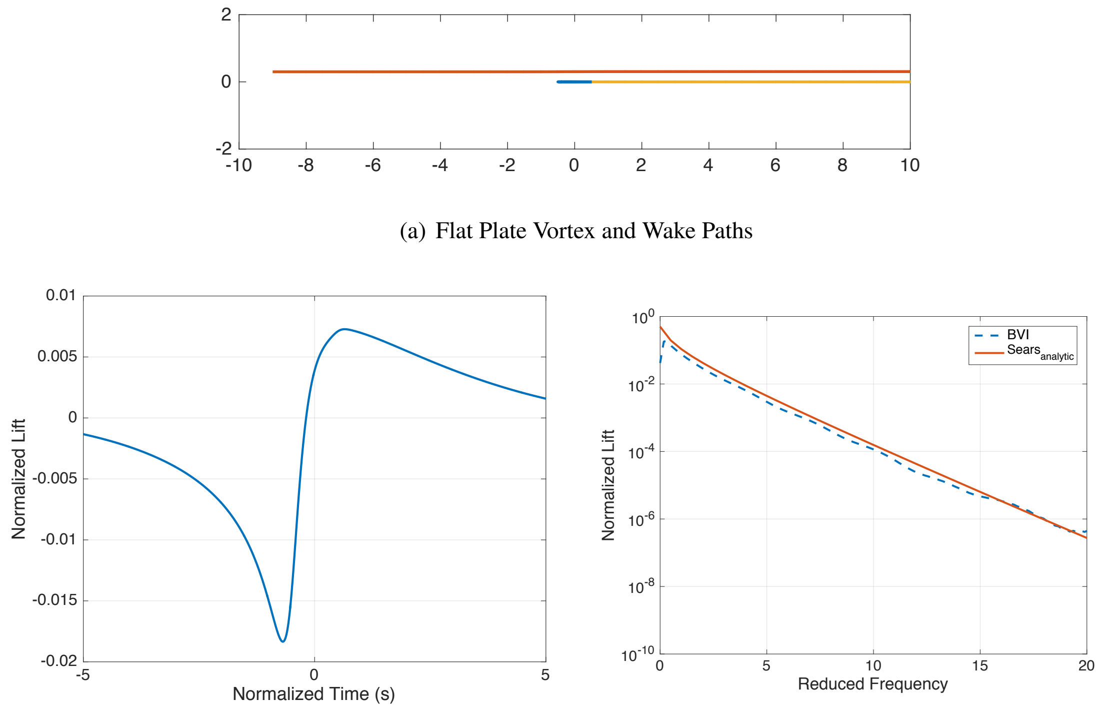
This lift is determined from the unsteady surface pressure defined by the unsteady Bernoulli?s relation: $C_p = 1 - 2\dot{\phi} - V^2$ where ϕ is the velocity potential and V is the velocity magnitude on the airfoil surface. The unsteady pressure is integrated along the discretized airfoil body to obtain an unsteady lift value at each time-step. Shown in figure 1a shows the vortex trajectories from a BVI simulation where the imposed vortex has strength 0.02 and is placed 9 chordlenghts upstream and 0.3 chordlengths above a flat plate. Figure 1b shows the unsteady lift signal in time, and figure 1c shows the Fourier transform of the time signal. The transformed result is plotted against reduced frequency $k_1 = \frac{2\pi fc}{2U}$.

The relationship between the BVI problem and the gust problem has been previously described by Widnall[3]. It was shown that the unsteady response to a unit gust can be recovered from the unsteady response to a unit vortex passing via

$$c_{l_{gust}}(k_1) = c_{l_{BVI}}(k_1)e^{kh} \quad (1)$$

where $k = \frac{2\pi f}{U}$ and h is the closest passing distance of the vortex to the airfoil[4]. Figure 1c shows the scaled gust response based on the Sears function which is valid for the flat plate gust interaction problem. The agreement is perfect as expected. If the vortex passes the flat-plate too close (e.g.< 0.4 chordlengths) then the BVI and gust results do not compare well. In this case, the panel method gives rise to inaccuracy in the unsteady lift calculation specifically as the vortex passes over the trailing edge.

This demonstrates that the current BVI calculation method works well for the benchmark case of the vortex passing the flat plate.



(a) Flat Plate Vortex and Wake Paths

(b) Airfoil Unsteady Lift

(c) Flate Plate Lift Spectrum vs. Sears

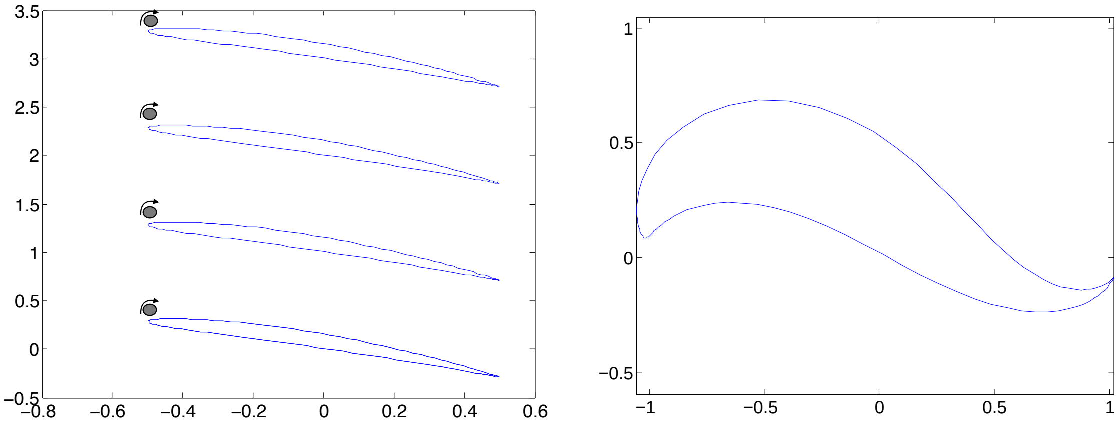
Figure 1. Blade Vortex Interaction Simulation for Flat Plate.

b. Extension of BVI calculation to a Cascade

A mapping given by Howell[11] and Thwaites[12] that transform an infinite cascade into a single object was utilized by Bhimarasetty and Govardhan[9] to compute the mean flow around a cascade of airfoils. Figure 2 shows the transform of a cascade of NACA6412 airfoils at 13 degree stagger into a single object. In the transformed plane, the freestream flow is represented by a source and vortex located at (1, 0) and a sink and vortex located at (1, 0). Points far upstream of the cascade transform into basically the single point (1, 0) and points far downstream of the vane transform into the single point (1, 0).

Steady results for various cascade geometries were obtained using this method and validated method against experimental data[13]. For example, Figure 3 shows the case of a NACA 65-410 airfoil at two 1/(gap-to-chord) ratios (σ). Good agreement in the steady surface pressure is obtained.

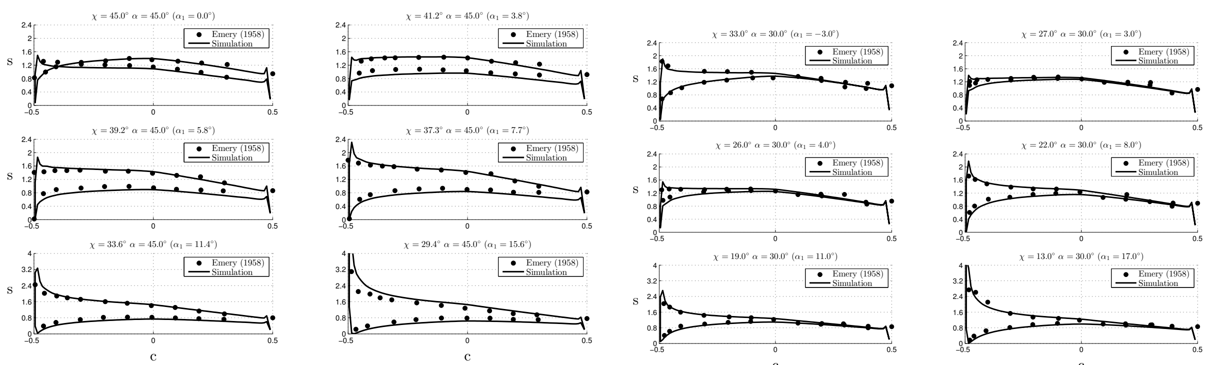
When one considers imposing a vortex upstream of the cascade, the transformation imposes a gap-to-gap symmetry of the vortex as shown in Figure 2. This imposes a 0 interblade phase angle for the disturbance. In practice this means that the method would only be valid for turbomachinery applications with the same number of rotor blades as vanes. This blade count relation is not of interest. but nonetheless it allows for some exploration into cascade interactions. In this work comparisons will only be made to gust-cascade results for the 0 interblade phase angle case.



(a) Cascade

(b) Transformed shape

Figure 2. Cascade of NACA 6412 (left). Shape of single body in transformed plane (right).



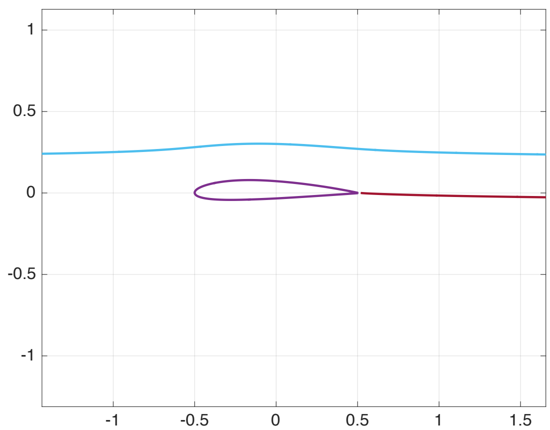
(a) $\sigma = 0.5$

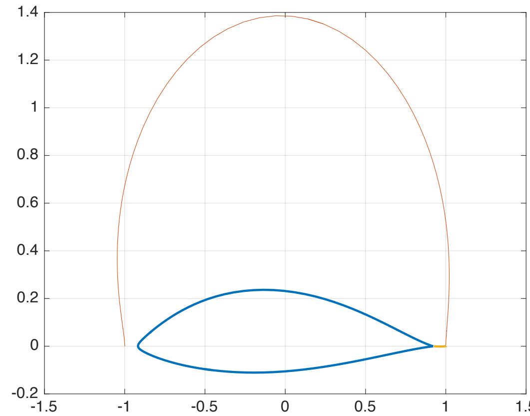
(b) $\sigma = 1.0$

Figure 3. Blade-surface pressure distributions of NACA 65-410 airfoil for the cascade configuration. Data from Emery et. al.[13]

For the cascade BVI model, the method described for the single airfoil calculation in which the vortex path and wake path are predetermined using mean flow convection is applied again. The paths are determined in the cascade frame and the points are then transformed into the cascade space. Figure 4 shows the path of the vortex and wake for a NACA 2412 airfoil as a single airfoil. Also shown is the transformed geometry along with the transformed vortex path and wake points. The Fourier transform of the unsteady lift of the cascade was found in a similar way to the single airfoil results.

At low Mach number and large gap-to-chord ratios, the cascade response should reduce to the single airfoil response. This is the case as seen in Figure 5. As the gap-to-chord ratio decreases, the results have to be compared to flat-plate cascade results. The integral equation solution described by Ventres[15] is used for verification here. Figure 5 shows that the code matches Ventres reasonably well for the higher cases gap-to-chord cases but deviates significantly as the ratio reduces to 1.0.

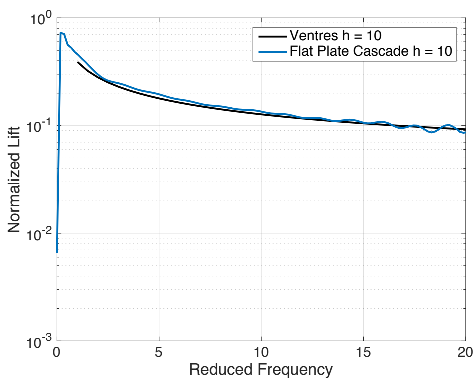




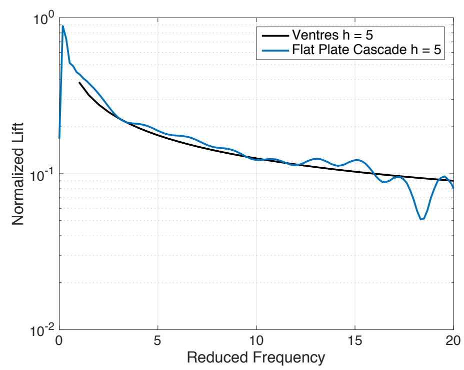
(a) Large gap-to-chord spacing

(b) Small gap-to-chord spacing

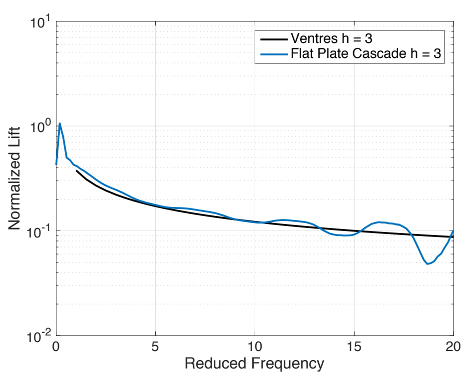
Figure 4. Cascade vortex and wake paths for gap-to-chord raios of 10 (left) and 1 (right)



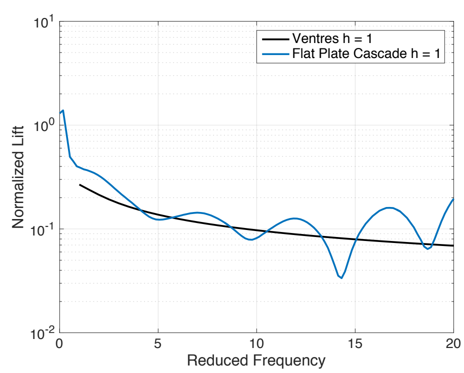
(a) h = 10



(b) h = 5



(c) h = 3



(d) h = 1

Figure 5. Verification of cascade bvi (blue) against Ventres (black) for different gap-to-chord ratios.

III. Results

a. Further verification of BVI calculation via single airfoil cases

Simulations for a case of the single, flat-plate, airfoil, simulations with different vortex passage heights were run. The resulting BVI lift spectra were scaled via an e^{kh_a} value in order to collapse the results to those of the case with the largest vortex passing distance. The effect of airfoil thickness and camber were considered next. Figure 6 shows the BVI response for various NACA airfoil geometries. The previously reported[4] reduction in the lift response with increased airfoil thickness and camber are reproduced. The scallops seen in the thicker airfoil cases have also been reported by others. They have been associated by others with discretization issue in where there exists a panel size mismatch between the trailing edge panel size and the distance between the trailing edge and first wake point[16]. In this implementation the scallops *are* influenced by the form of the lift response as the vortex passes the trailing edge; however, the scallops have not been determined to be solely dependent upon this factor. These verifications give confidence in the general panel method that is currently being used.

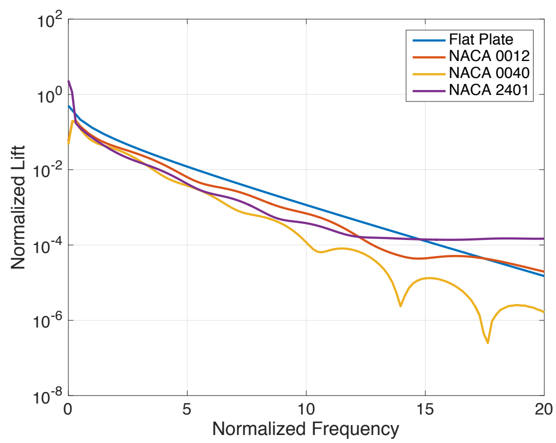


Figure 6. Single airfoil BVI lift spectrum

b. Effect of cascade airfoil shape

The gap-to-chord spacing of 3 was shown to provide good comparisons between the BVI and gust results for the flat-plate cascade case and while not being pertinent to turbomachinery applications, in order to provide an analysis without any sizable influence of the scallops on the lift spectrum this gap-to-chord ratio was used for the shape study. In all of the cases presented in this section, the imposed vortex is place 9 chordlengths upstream at a vertical offset from the cascade airfoil of 0.2 chordlengths. Figure 7 shows the effect of cascade airfoil thickness and camber on the cascade response. An increase of thickness to 6% does not greatly affect the response. Increasing to 12% thickness gives as much reduction in the lift response as was seen in the single airfoil case. Increased camber increases the response as lower reduced frequencies before significantly reducing the response beyond a k_1 of 3. While the results above show that the BVI cascade method reproduces basic trends for the cases considered, it is of interest to consider more realistic spacing, rotor vane counts, and higher flow Mach number. Figure 8 shows the response of the flat-plate cascade at a higher Mach number as predicted by the Ventres method. Cascade resonances are apparent. The Figure also shows the effect of a nonzero interblade phase angle. The flat-plate cascade response at low Mach number but with wave number specification $k_2 = k_1$ exhibit an oscillatory behavior with increased wave number due to the phase effects.

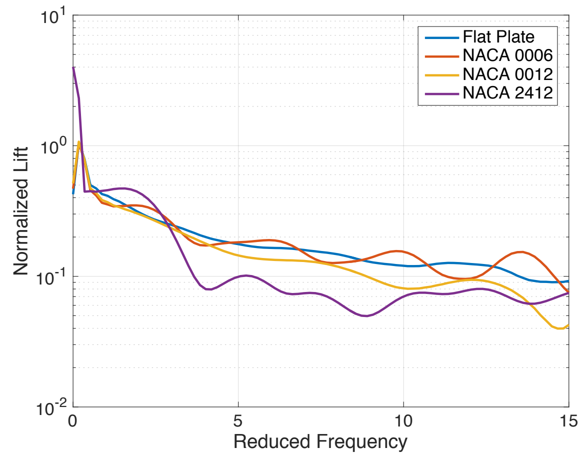
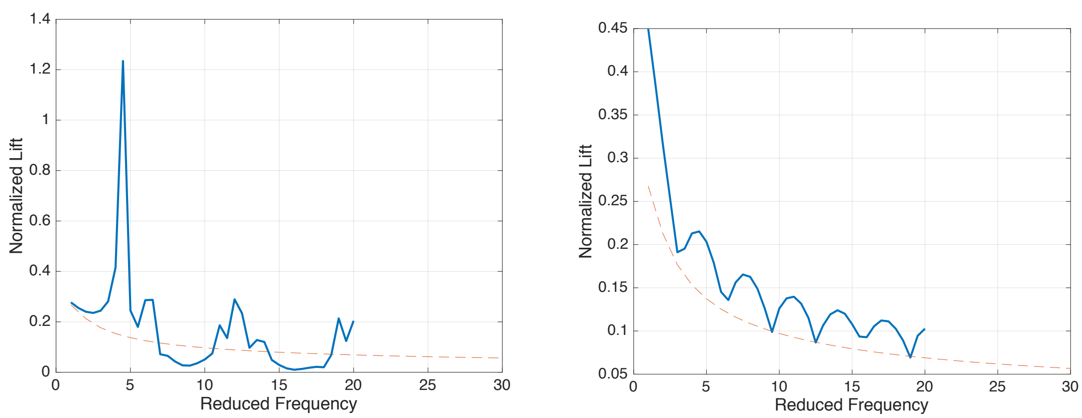


Figure 7. Cascade bvi lift spectrum for various geometries

As mentioned in Section II, a boundary element method that incorporates the subsonic flow effects could be used in place of the basic panel method to perform the BVI simulations [17]. However, it is still unclear how to introduce the interblade phase angle effect. A modified boundary condition could be imposed on one side of the cascade airfoil in the transformed plane. This would counteract the periodicity in the transformation but the actual boundary condition specification would be heuristic.



(a) Mach number = 0.4, h = 1, k2 = 0

(b) Low mach number, h = 1, k1 = k2

Figure 8. Flat plate cascade gust results from ventres. Incompressible, 0 interblade phase angle, dashed red. Higher mach number effect left. Nonzero interblade phase angle right.

IV. Conclusions

We consider a BVI cascade model as a potential method for for incorporating real vane geometry in a turbofan broadband noise model. The work is motivated by the desire to eliminate the flat-plate vane assumption currently used in low-order broadband noise models for fan-stage, rotor-stator interaction noise. An unsteady panel method was developed to perform the blade vortex interaction simulations. It has been shown that the current BVI calculations are able to produce the single airfoil response trends for airfoils with thickness and camber.

A method for considering a vortex (or more accurately a set of vortices) passing through a cascade of airfoils has been developed. The cascade BVI calculations are able to reproduce the results of Ventres for high gap-to-chord ratios but deviate ratios of 1 or less. The model is able to reproduced the expected trends for the effect of cascade airfoil geometry when the gap-to-chord ratio is larger than 1.0. Currently, simulations for realistic Mach numbers are not feasible but it is assumed that this restriction can be easily addressed by using a more sophisticated boundary element method. The transformation used in the model assumes a completely periodic BVI simulation from blade to blade, i.e. 0 interblade phase angle.

While the model has some positive attributes, it seems that the inherent periodicity of the incoming disturbance and the inability to obtain accurate results at realistic gap-to-chord ratios mean it is not worth pursing for use in the low-order turbomachinery noise modeling.

Acknowledgments

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