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Analysis of Mean Loading Effects in Fan Broadband Noise Simulations

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A low-order method for predicting broadband interaction noise downstream of a fan stage in a turbofan engine is extended to include more realistic vane geometry. Vane thickness and camber are included by utilizing an asymptotic unsteady gust response method. Currently, a single airfoil model for the exit guide vanes is used to obtain preliminary insight into the effect of real geometry on the broadband noise prediction. In this work, the Source Diagnostic Test geometries are used and the results are compared to the experimental data. It is shown that results produced using the single airfoil flat-plate gust response model do not match those produced using a flat-plate cascade gust response model. However, the sound power trend across rotor speeds is still predicted. Comparison between results obtained using the flat-plate single airfoil and the real geometry airfoil response models show that including both thickness and camber only moderately affects the sound power level. Further investigation is needed to fully describe the results from a physical point of view.

I. Introduction

Many hybrid computational methods currently used to predict the broadband noise associated with wake-vane interaction in the fan stage of a turbofan engine rely on a two step computational process. First the response of the fan exit guide vanes (FEGVs) to multiple individual gust disturbances is computed and then the broadband sound power levels in the duct due to the interaction is calculated through synthesis of the individual gust responses with a wake turbulence model and a basic duct propagation methodology.[1–4] The hybrid methods currently model the exit guide vanes as strips of flat-plates whose unsteady response to an incident gust can be calculated semianalytically[4] or with asymptotic[2] techniques. In this paper, the effect of extending the model to include real vane geometry is explored.

The previously described RSI framework[1,4] for computing fan broadband noise provides the platform and the gust response model is updated in order to incorporate effects of real geometry. In this paper, a first step towards the full implementation of vane geometry is described. The exit guide vane unsteady gust response will be approximated via the unsteady response of a single, real-geometry vane. In the future, the guide vane unsteady gust response will be approximated via the unsteady response of a cascade of real-geometry vanes.

The Source Diagnostic Test (SDT)[5,6] is used for benchmarking the results in this paper. Both the baseline vane and low count vane geometries are considered. As well, the three rotor speeds: approach, cutback, and takeoff are modeled.

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Section II will describe the RSI framework briefly and provide a discussion of the necessary modifications to the theory to account for the real geometry effects. A comparison between predictions based on the flat-plate cascade and the single airfoil unsteady response models will be shown in order to provide a baseline for the results obtained with the real geometry single airfoil model.

II. Method

The RSI framework for predicting broadband FEGV noise begins with an assumption that the rotor wake turbulence is convected by the mean wake flow and can be viewed as a combination of Fourier components. Each component can be modeled as a three-dimensional gust disturbance of a specified frequency and wave number. The amplitude of each gust is specified by the turbulence spectrum. The full vane response to each gust is created using a strip theory in which each strip is considered independently. In the original RSI, the acoustic pressure response to the convected gust at each strip was calculated based on a two-dimensional semianalytical solution for the response of a cascade of flat-plate vanes to a gust.[7] (The calculation of the vane strip response to a gust will be termed the "core solver" portion of the RSI method throughout this paper.) Once the unsteady surface pressure on each strip is known it is appropriately weighted by the inflow turbulence spectrum and used to compute the acoustics downstream of the vane via the Green's function for a cylindrical annulus. It is noted, that the original RSI formulation included the variation of the turbulent kinetic energy across a rotor wake passage in the inflow turbulence model. It was later shown that the final results for the exhaust duct broadband noise were only slightly lower at high frequency when one used the average passage value of the turbulent kinetic energy.[4] Thus, the results reported in this paper only model the average passage value at each radial location. It is also noted that the version of RSI used in this work includes the effect of a spanwise gust component. Finally, a pre-processor is used in order to determine frequencies that are non-singular in the Green's function model for the acoustic pressure in the duct.

In order to accommodate the inclusion of real geometry effects, the implementation of the Green's function method was altered to allow for integration on the surface of the real vanes. Details concerning this method have been presented previously.[8]

Because hundreds of thousands of wave-number frequency gust combinations are used to compute the broadband response, the core solver must be efficient. Therefore, an asymptotic gust response method has been selected. It is planned that the asymptotic method for determining the unsteady pressure on a cascade of airfoils described by Peake and Kerschen[9–11] will be used. However, as a first step, an asymptotic method, similar to that described by Ayton and Peake,[12] and that extends Myers and Kerschen[13] to real geometry airfoils, will be used to predict the unsteady response of a *single* real geometry, lifting airfoil, to a gus. This will be used to model the unsteady pressure response of the vane at each strip. The asymptotic model requires that the mean flow be known. A panel method based mean flow solver has been created to work in conjunction with the asymptotic method.

III. Flat-plate cascade vs. flat-plate airfoil model

In order to put into perspective the effect that including vane geometry has on the predictions when the vane response is approximated using single airfoil theory, an initial comparison is in order. That is, the prediction obtained using a flat-plate cascade model should be compared to the prediction obtained using a flat-plate single airfoil model. To accomplish this, the flat-plate cascade unsteady response code that forms the core solver of the original RSI method was replaced by a flat-plate airfoil unsteady solver based on Possio's semianalytical formulation.[14] Then, as a preliminary validation for use of the asymptotic response solution, the flat-plate airfoil gust response was computed using the asymptotic method.

The results using the various core solvers for the SDT baseline vane case at approach rotor speed are shown in Figure 1. The trailing edge stagger angle was selected for use with the cascade solver. The trailing edge stagger angles are very close to zero for all strips from hub to tip. As such, results obtained with the flat-plate single airfoil solvers will correspond most closely to this cascade geometry because the single airfoils mimic vanes with zero stagger angle. The figure shows differences in the prediction from the two models at both the low and high frequencies. The trend is opposite in the two frequency ranges with the single airfoil giving lower power values at the high frequencies and higher values at the low frequencies. The results also show that the asymptotic single airfoil response method gives results in very good agreement with the Possio single airfoil results. The slight increase in overall power at most frequencies predicted with the asymptotic method is most likely due to limitations in the numerical implementation of the Possio method which leads to an underprediction of the lift at higher wave numbers. In 2006, Cheong *et al.* presented a fan broadband calculation in which they obtained the same predictions at higher frequencies when using both a cascade response model and a single airfoil response model.[15] The results in Figure 1 do not reproduce this result. For the SDT, the gap-to-chord ratio ranges from 0.4 to 0.83. At these very small values, the single airfoil gust response underpredicts the unsteady lift as compared to the cascade response until reduced frequencies of over 60. The reduced frequencies represented in the present calculations range from 3 to 86. However even at the highest frequencies where the single airfoil and cascade results compare well, this is only true for zero spanwise wave number. As spanwise wave number is included, then the single airfoil model under predicts the response again even at high reduced frequencies. Therefore, it is reasonable that for the SDT case being considered, the findings of Cheong *et al.* will not apply.

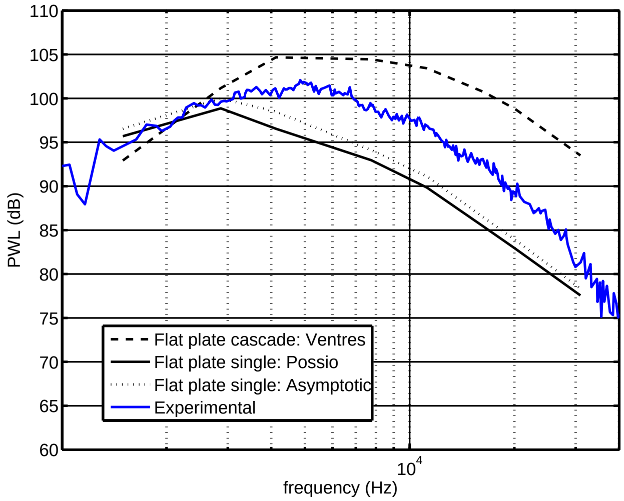
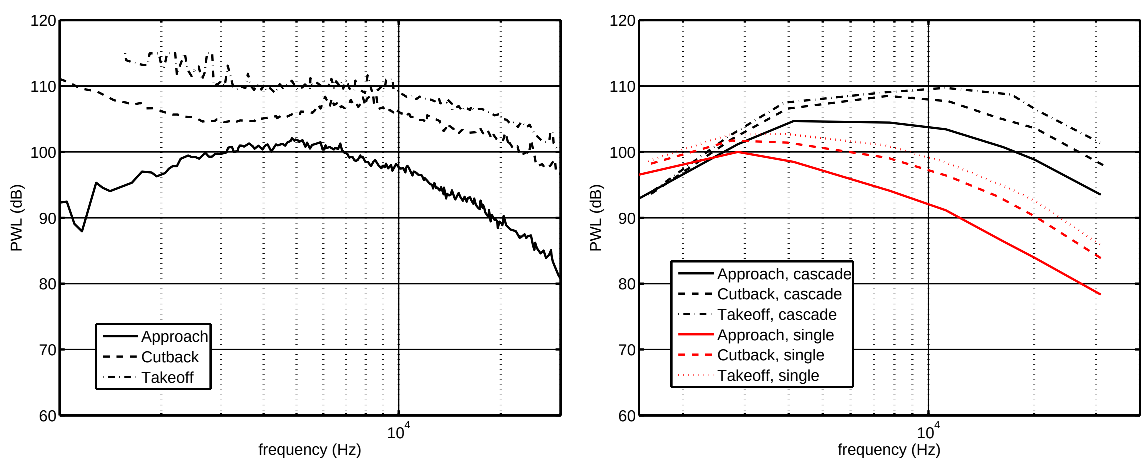


Figure 1. Exhaust duct sound power level for SDT baseline vane at approach rotor speed computed with a cascade response core solver (using trailing edge stagger) and with two single airfoil response core solvers based on Possio and the asymptotic method.



(a) Experimental results

(b) Computed results.

Figure 2. Exhaust duct sound power level for SDT baseline vane at three speeds computed with a flat-plate cascade response core solver and with a flat-plate single airfoil response core solver. Hot-wire data was used to describe the flow quantities in RSI and the cascade stagger was selected to match the trailing edge stagger of the real vane.

It is also noted that the results obtained using the cascade response model are higher than the experimental results, and higher than those predicted by Posson *et al.*[2] for the SDT baseline vane case. It is surmised that this difference is due to the fact that the current model does not include an annular correction in the vane response calculation like that in Posson's method.

Although the prediction utilizing the single airfoil response core solver is quite different than that obtained when the cascade is modeled, the single airfoil model does capture the trend with rotor speed fairly well. Figure 2 shows the predictions obtained with the flat-plate cascade and the flat-plate single airfoil methods at approach, cutback and takeoff rotor speeds. Both core solvers provide the same reasonable trend prediction. Finally, the trend in the broadband acoustic power for two vane geometries: baseline and low count, was explored. Figure 3 shows the predictions obtained with the flat-plate cascade and flat-plate single airfoil response core solvers for the two vane geometries. In the RSI method, when the vane is modeled as a flat-plate airfoil or cascade, it is assumed that the flow is perfectly aligned with the flat-plate chord. For the cascade, the stagger angle sets the angle of the chord and it has been chosen to match the trailing edge stagger of the real vanes. Here it is seen that the cascade model does a better job capturing the trend across vane configurations. The single airfoil does not predict the lower frequency similarity between the two configurations.

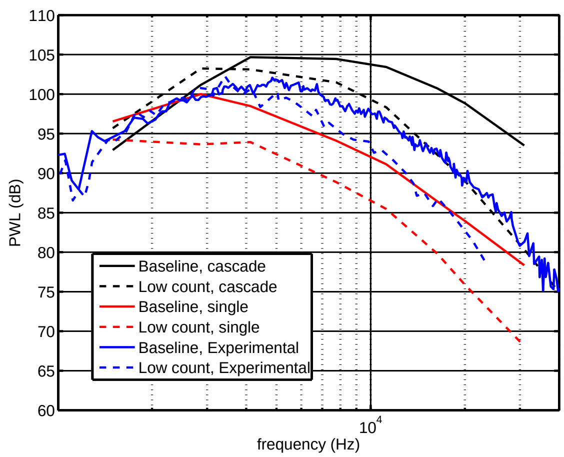


Figure 3. Exhaust duct sound power level for SDT baseline and low count vanes at approach speed computed with a flat-plate cascade response core solver and with a flat-plate single airfoil response core solver. Hot-wire data was used to describe the flow quantities in RSI and the cascade stagger was selected to match the trailing edge stagger of the real vane.

IV. Addition of mean loading

Figure 4. SDT baseline vane geometry.

The baseline vane is far from a flat-plate as seen in Figure 4. It is nominally 10% cambered and is 7% thick. The experimental flow measurements indicate that the flow is at a relatively high angle of attack to the vane also. Capturing the exact geometry and flow conditions is not possible in the current method. In particular, the angle of attack is too large to work effectively in the asymptotic response model which is based on thin-airfoil theory. However, the effect of geometry has still been considered to the extent possible within the current model.

First, thickness is considered. A seven percent thick airfoil is modeled at each spanwise strip. The flow is considered to be perfectly aligned in the axial direction with magnitude that matches the SDT experimental flow data. The case is identical to the flat-plate airfoil case and the flat-plate cascade case with zero trailing edge stagger except for the thickness. The SDT baseline vane chordlength and number of vanes has been simulated here. The broadband sound power level in the exhaust duct is shown in Figure 5.

At approach speed, thickness slightly increases the high frequency power and decreases the low frequency power. The results for the cutback and takeoff cases show a much stronger effect of thickness than is expected. The accuracy of this result and any related physical mechanism will be investigated in the future.

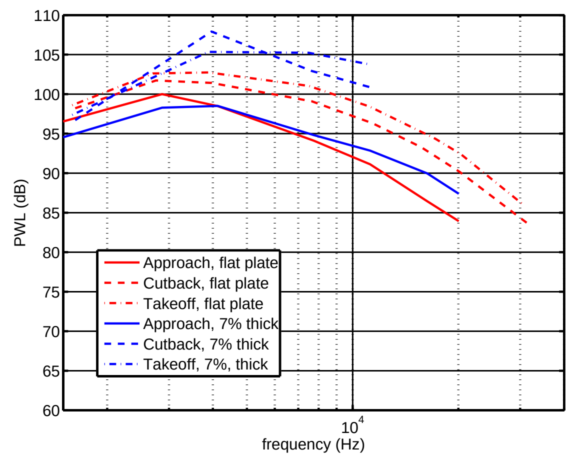


Figure 5. Effect of vane thickness on downstream sound power level. Flow parameters match the SDT at the three wheel speeds.

Camber can be added to the geometry to match that of the SDT baseline vane. A sketch of a section of the baseline vane with its actual leading and trailing edge stagger angles is shown in Figure 6. This vane section is 7% thickness, has 9% camber, and its chord is at a 10.5° angle to the axial direction. The inflow is at about 30° to the horizontal. This would mean that the flow is at an angle of attack of almost 20°. The asymptotic response method does not provide a solution for this high of an inflow angle. For the present calculations, it is assumed that the inflow is exactly aligned with the chord of each span wise section. So in effect, no angle of attack is considered. This is similar to the assumption made when the flat-plate response model is used. It is always assumed that the flow is perfectly aligned with the chord and the chord alignment is set by the choice of stagger angle (e.g. leading edge, mid chord, etc.). Figure 7 compares the results obtained using the gust-response core solver for the flat-plate single airfoil; the thick, single airfoil; and the thick, cambered single airfoil geometries. The symmetric geometries are placed with their chord in the axial direction mimicking zero stagger angle. The cambered geometry is set to match the actual SDT baseline vane geometry. Thus the trailing edge angle measured from the axial direction is close to zero and the leading edge angle ranges from 38° to 30° depending on the spanwise location.

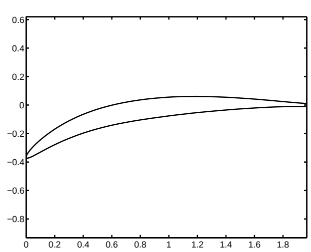


Figure 6. SDT baseline vane geometry with given leading and trailing edge stagger.

The inclusion of camber does not change the results for the approach speed significantly. It tilts the spectrum a bit giving lower levels at low frequency and higher levels at higher frequencies as compared to the symmetric model. The tilt is opposite that found when the leading edge stagger angle is selected for use in the flat-plate simulation as opposed to the trailing edge angle. This is a bit surprising because the unsteady response is strongest near the leading edge. Therefore it was surmised that matching the real vane geometry would tilt the spectrum slightly in the other direction. Further comparisons must be made in order to determine if indeed the spectral tilt is the main effect of including camber. In particular, the effect of camber on the predictions at higher wheel speeds must be investigated.

V. Conclusions

The Source Diagnostic Test vane geometries and flow conditions have been used to perform an initial investigation of the impact of including more realistic geometry models in a hybrid broadband noise simulation. The prediction of broadband interaction noise downstream of the exit guide vane is the end goal of this research. The geometry effect is incorporated through an asymptotic gust-response model for real geometry airfoils. This gust response model replaces the more simple flat-plate gust response.

It is shown that a single airfoil model of the exit guide vane leads to an under prediction of the exhaust duct sound power level when compared to a prediction based on a cascade model of the vanes. However, the sound power level trend with wheel speed is simulated with reasonable accuracy using the single flat-plate airfoil model. The trend with vane count is not as accurately captured with the single airfoil model.

Then comparisons are made between predictions obtained with the flat-plate single airfoil model of the vane and more realistic single airfoil geometries. First, the effect of thickness is considered, and it is shown that the inclusion of thickness affects the prediction at cutback and takeoff wheel speeds more dramatically. The reason behind this effect still needs investigation.

Second, camber and thickness are included to match the actual geometry of the SDT baseline vane. Results at the approach wheel speed indicate that the camber tilts the spectrum a bit. The physicality of the spectrum change will be investigated further in the future.

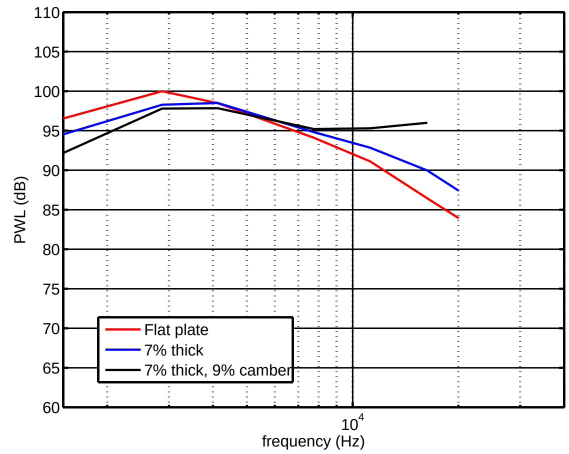


Figure 7. Effect of vane camber on downstream sound power level. Conditions chosen to match the SDT baseline vane case at approach speed.

Acknowledgments

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