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MODELING THE NORMAL MODES AND ACOUSTICS OF A JET ENGINE

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INTRODUCTION

There are at least two challenges that the jet engine noise community is currently facing. One challenge is due to existing engines that are being extended to higher power ratings without increasing the passive noise control treatment area. The second challenge comes about with the increasing trend to go to ultra-high bypass engines. This increases the importance of the fan tone noise and at the same time, due to decreased duct surface area, makes passive noise control treatment more difficult to apply.[1] These two challenges combined with increasing noise regulations from the FAA on jet engine noise have caused researchers to look into additional noise control methods besides passive noise control for decreasing engine noise. One method which is being investigated is active noise control (ANC) of fan noise from the turbofan jet engine. Fan noise is an ideal target for ANC because it is relatively low in frequency and is sinusoidal in nature.

A computer model of a simplified turbofan geometry using I-DEAS and SYSNOISE has been developed at Brigham Young University. An ANC simulation using the model is performed. This ANC algorithm is designed to minimize the modal response of the acoustic field inside the engine duct. The objective of the research is to first match prior experimental results obtained for the simplified geometry. The model can then be used to predict the ANC performance for a more realistic geometry.

THE MODEL

The simplified turbofan geometry of the model is based on the geometry of the test rig located at NASA Glenn Research Center. Figure 1 shows a schematic diagram of the test rig. The model was generated and meshed using I-DEAS. Four- node quadrilateral elements which are on average 0.055 m in length were used to mesh the boundaries of the engine. Using the six elements per wavelength criterion suggested for the acoustic boundary element, the model results should be valid up to 720 Hz. The outer wall of the outer duct was left off to reduce the number of elements and decrease the run time (see Figure 2). Since the acoustic field inside of the duct is of primary concerned in this research project, it was felt that this omission would not significantly change the results. The mesh is then imported to SYSNOISE to determine the acoustic field inside and around the engine duct. Due to the large number of nodes and the geometry of the problem, the indirect boundary element method (IBEM) in the frequency domain was chosen. IBEM is faster for larger meshes and can simultaneously calculate the acoustic field both inside and outside of the engine duct. The frequency

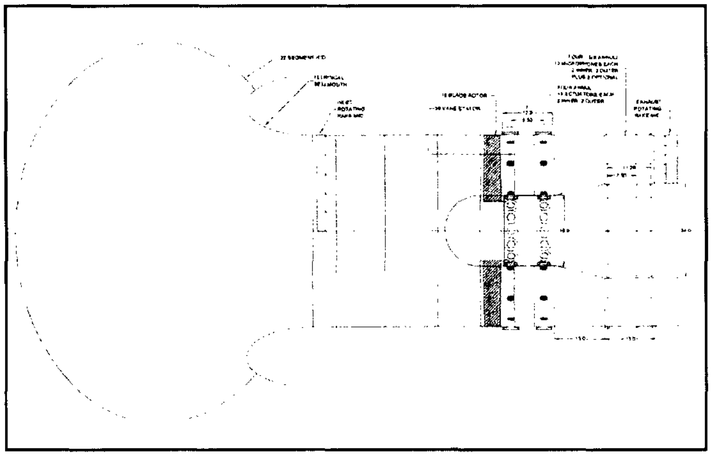

Figure 1. *Schematic diagram of test rig at NASA Glenn Research Center [1].*

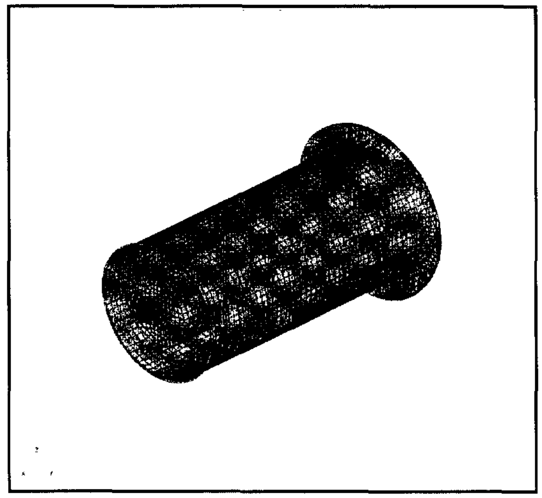

Figure 2. *Boundary element mesh of the test rig geometry.*

domain rather than the time domain was chosen for calculation speed. The duct walls and inner core walls are treated as rigid walls and the pressure jump at the two open ends of the duct is set to zero.

The engine rotor is modeled using 256 spherical sources (acoustic simple sources). These sources are arranged in a single ring in a plane at the rotor position along the duct. The sources have the same magnitude but are phased so that the azimuthal m = 2 mode is excited. It was determined in tests performed at NASA Glenn Research Center that the m = 2 mode is the major contributor to fan noise.[1] Figure 3 shows a spatial Fourier decomposition of the acoustic field generated by SYSNOISE at the plane of the rotor. The m = 2 mode is higher by 15 to 20 dB than the other existing modes. This agrees qualitatively with experimental data obtained on the test rig as shown in Figure 4.

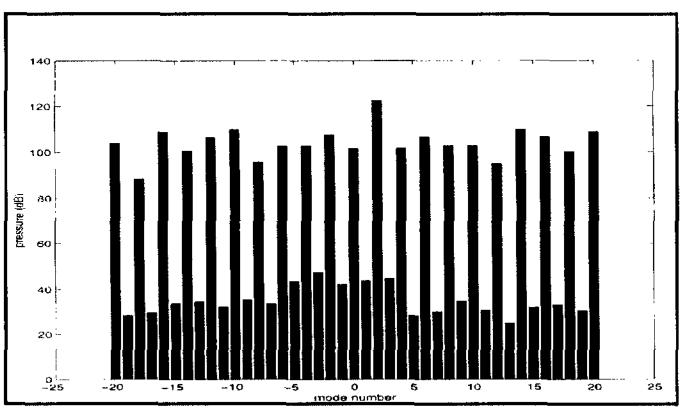

Figure 3. *Spatial Fourier decomposition of fan noise as generated by SYSNOISE showing the m = 2 mode is about 15 dB higher than the other modes.*

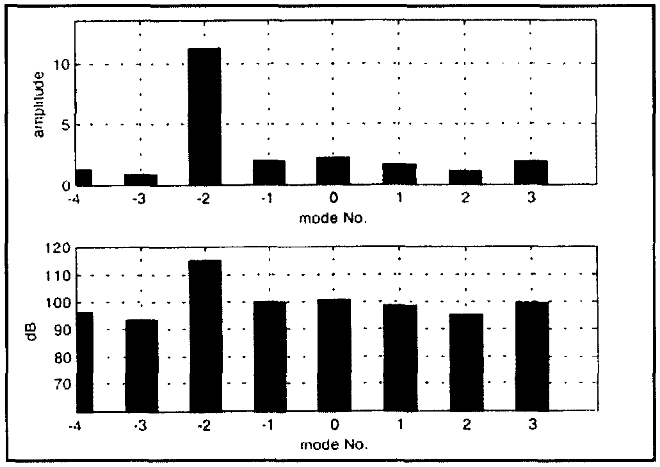

Figure 4. *Spatial Fourier decomposition of fan noise at 1300 RPM obtained from test rig showing the m = -2 mode is about 20 dB higher than the other modes [1].*

Field points are placed two millimeters off of the outer duct wall inside the duct. The field points serve as error microphones for the ANC simulation. There are five microphone rings in the model but only two microphone rings at a time are generally used. There are 10 error microphones (or field points) per ring equally spaced azimuthally. The microphones of one ring are azimuthally offset from the microphones of the neighboring rings.

Spherical sources (simple sources) located three millimeters off of the outer duct wall inside the duct are used as the control actuators. There are four actuator rings but usually only two are used for any particular run. Each ring has 16 actuators. The spacing of adjacent rings is offset from the neighboring rings in a manner similar to the error microphones. Because the sources are so close to the boundary, mirror spherical sources in the same location as each of the actuator sources are used. These mirror sources have identical magnitudes and phases as the sources they mirror.

After the sources and field points are set up, it is necessary to determine the acoustic response of the duct. To do this a matrix corresponding to the propagation path matrix, C_m, is calculated. Its individual components, $C_{m,ij}$ consist of the transfer function from the j^{th} actuator ring modal amplitude for m = 2 to the i^{th} sensor ring modal amplitude for m = 2. The matrix is obtained by turning off all of the rotor sources and running the model with only one actuator ring on at a time. The actuator sources of that ring are phased so as to excite the m = 2 mode. The response of the microphone rings for each individual actuator ring is then used to generate a C_m propagation path matrix which is used in the ANC update equation.

Once the C_m matrix has been calculated, a run can be made. For the first iteration of the run, the actuator sources are turned off and only the rotor sources contribute to the noise. The pressure at the error microphone field points is used to update the control algorithm and determine what the actuator output should be. The pressure must be spatially Fourier decomposed in order to determine the m = 2 contribution the overall noise. The m = 2 pressure contribution is then used in the update equation:

$$y_m(k) = y_m(k-1) - \mu\left[C_m^H C_m\right]^{-1} C_m^H e_m(k-1) \quad (1)$$

where $y_m(k)$ is the control output modal amplitude vector for the k^{th} iteration, μ is the convergence parameter, C_m is the propagation path matrix described above, $e_m(k)$ is the error signal modal amplitude vector for the k^{th} iteration, and the superscript H denotes Hermitian transpose. The ANC algorithm uses Newton's method to update the actuators. The control output signal for each ring is converted from modal amplitude to individual actuator signals by multiplying the modal amplitude by the appropriate Fourier coefficients:

$$u_{ni}(k) = y_{mn}(k)e^{j2\pi mi/16} \quad (2)$$

where m is the circumferential mode index, n is the actuator ring number, i is the actuator index for each actuator in the n^{th} ring, $u_{ni}(k)$ is the individual actuator signal, k is the time block number, and 16 actuators per ring are assumed. Random noise is added to the individual actuator signal magnitude and phase to simulate the noise present in real microphones and actuators. With the updated magnitude and phase for the actuators, another iteration is performed and the process is repeated until the model converges or diverges.

EXPERIMENTAL RESULTS

A modal control system, as described above, was implemented on the NASA test rig at NASA Glenn Research Center and control of the m = 2 mode was achieved in test runs. At 1300 RPM (693 Hz) using the two microphone rings closest to the inlet opening and actuator rings closest to the fan, 16 dB attenuation was achieved.[1] The use of 2x2 control (two microphone rings and 2 sensors rings) was effective until the cut-on RPM of the 3rd radial of the m = 2 mode is approached as seen in Figure 5. 2x2 control then becomes ineffective, most likely due to the strong presence of the evanescent 3rd radial mode. When 3x3 control was used, the m = 2 reductions are again significant (see Figure 5). These controller results were compared with the pressure results obtained from NASA's rotating rake which uses the doppler effect and least squares fit to determine the pressure components of the field.[2, 3] Results obtained from the controller varied in agreement when compared with the results from the rotating rake. Generally the results agreed well (within 1 - 2 dB), however, there were cases with less agreement. There were times when the controller would indicate significant control had been achieved and the results from the rake indicated amplification or minimal control had been achieved.[1] It is hoped that the computer simulation can provide insight into the reasons behind the discrepancies.

SIMULATION RESULTS

The multi-modal ANC algorithm converges using the computer simulation. For 2x2 control at 693 Hz using the microphones closest to the inlet opening and actuator rings closest to the fan, the m = 2 mode is decreased by roughly 40 dB. Using microphones closest to the fan causes the m = 2 mode to be decreased by roughly 48 dB. However, when the pressure in a plane perpendicular to the duct axis is examined (similar to the role of the rotating rake in the experimental results), little or no control is found. Additionally, it has been discovered that the higher order radial modes which should be evanescent at 693 Hz, do not decay in the duct. Currently, we are looking for ways to get around this problem because the controller and more realistic results depend on realistic simulations, such as evanescent modes which do not propagate. We are hopeful that our model is correct and are working with the software company to get the issue resolved.

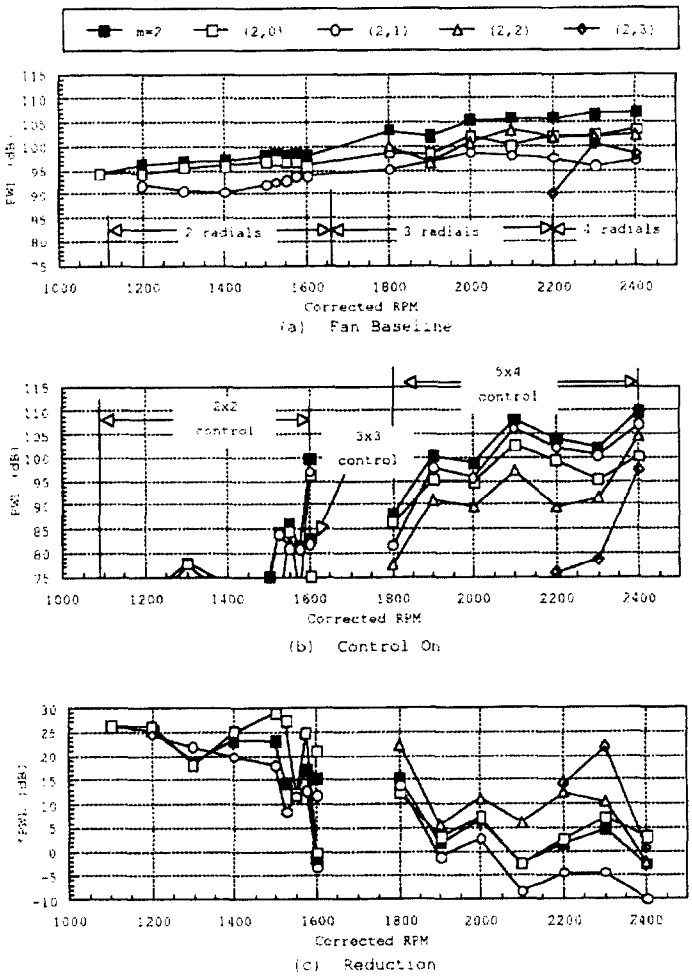

Figure 5. *ANC controller results obtained from test rig at NASA Glenn Research Center [1].*

CONCLUSIONS

A computer simulation of multi-modal ANC of the fan tone in a turbofan jet engine duct has been developed to allow additional insight into the acoustic modes in the engine duct. The algorithm uses Newton's method to reduce the m = 2 circumferential mode. Good results ranging from 15 to 25 dB attenuation were achieved in experimental test runs made at NASA Glenn Research Center. Attenuations of 40 to 48 dB were achieved in computer simulation runs, but the results are now being examined due to lack of agreement with values obtained using the pressure in a plane of the computer model duct. It was found that higher order modes, which are supposed to be evanescent, actually propagate along the duct. Assuming this issue is resolved, we plan to move to a more realistic engine geometry and apply ANC to that model.

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