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# Dipole Active Control of Wake-Blade Row Interaction Noise

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**In high-bypass turbofan engines, discrete-frequency tones are generated at blade-pass frequency and its harmonics by the unsteady interaction between the rotor blades and stationary strut and vane rows. Specific circumferential acoustic modes are generated, determined by the number of rotor blades and stator vanes. However, only certain modes propagate to the far field and result in the discrete-frequency noise received by an observer. This paper is directed at active control of this discrete-frequency noise through cancellation of the propagating acoustic waves. A series of experiments is performed in the Purdue Annular Cascade Research Facility configured with a 16-bladed rotor and either one or three airfoil stator vane rows. The active discrete noise control is accomplished utilizing a speaker–dipole arrangement around each stator to generate additional control, propagating acoustic waves that interact and cancel those generated by the rotor–stator interaction, with the control parameter being the phase angle between the rotor wake and the speaker–dipole. In both one- and three-airfoil stator vane row configurations, the active noise control system simultaneously attenuated all upstream- and downstream-propagating modes. The system was also demonstrated in a monopole configuration that also provided significant noise reductions in the three-airfoil stator vane row.**

## Nomenclature

$a_\infty$ = speed of sound
$\hat{e}_\eta$ = unit vector tangential direction
$k_\theta$ = tangential wave number
$k_\xi$ = axial wave number
$M$ = freestream Mach number
$M_\theta$ = tangential Mach number $M \sin \Theta$
$M_\xi$ = axial Mach number $M \cos \Theta$
$N_{\text{blades}}$ = number of rotor blades
$N_{\text{vanes}}$ = number of stator vanes
$n$ = rotor harmonic
$p$ = perturbation pressure
$\bar{p}$ = complex pressure perturbation constant
$U_\infty$ = mean axial velocity
$u$ = axial perturbation velocity
$\bar{u}$ = complex velocity perturbation constant parallel to blade row
$V_\infty$ = mean tangential velocity
$\bar{v}$ = complex velocity perturbation constant normal to blade row
$v$ = tangential perturbation velocity
$x$ = direction along chord
$y$ = direction normal to chord
$\theta$ = tangential coordinate
$\xi$ = axial coordinate
$\omega$ = frequency
$\Omega$ = rotor rotational speed

## Introduction

THE aeroacoustics of advanced gas-turbine engines is an increasingly important design issue. The primary noise sources for high-bypass engines are the fan, the low-pressure or booster compressor, and the low-pressure turbine. Their noise signatures include a broadband noise level, with large spikes or tones at multiples of blade-passing frequency. For subsonic fans, the acoustic spectrum discrete tones are usually 10–15 dB above the broadband level. Current engine noise control is usually a combination of source control and suppression. Source control involves increasing the axial spacing between adjacent blade rows and selecting blade and vane number combinations to produce cutoff. Source suppression is achieved with acoustic liners in the fan inlet, exit, and core exit ducts. These passive noise-control techniques will not provide practical noise suppression for the gas-turbine engine designs of the future.

An active noise-control technique was demonstrated by Thomas et al.,[1] in which a multichannel feedback control system was used to cancel noise of a JT15D turbofan engine. The noise was decreased for a range of ±30 deg about the engine axis, but was increased for all other angles. Active noise control for a centrifugal fan was demonstrated by Koopmann et al.[2] Noise reductions of up to 23 dB were observed for a technique in which vibrating plates and loudspeaker control sources were placed in the cutoff region of the fan casing. An aerodynamic noise-control approach directed at unsteady lift cancellation on an airfoil, thereby decreasing the noise generation, has been accomplished with oscillating flaps.[3]

For a turbomachine stage, a rotor, and stator in a duct, specific circumferential acoustic modes are generated, with these modes determined by the relative number of rotor blades and stator vanes. In addition, only some of these modes propagate to the far field. The propagating modes represent the discrete-frequency noise. Hence, to control far-field noise, it is necessary to control only these propagating pressure waves. This is accomplished by generating control-propagating waves that interact with those generated by the rotor–stator interaction.

Kousen and Verdon[4] developed a computational model based on the LINFLO model[5] for controlling wake–blade interaction noise by means of oscillating pistons. Also, Minter et al.[6] utilized a flat-plate cascade model to control wake–airfoil interaction discrete-frequency noise generated by subsonic blade rows through cancellation of the propagating acoustic waves, with the active noise-control techniques including oscillating leading- and trailing-edge flaps as well as airfoil surface-mounted oscillating pistons, all of which act as dipoles.

This paper is directed at active control of discrete frequency noise generated by subsonic blade rows through cancellation of the propagating acoustic waves. Experiments are performed in the Purdue Annular Cascade Research Facility configured with a 16-bladed rotor and either an isolated vane or a vane

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row with three airfoils. The active discrete noise control is accomplished utilizing a speaker–dipole arrangement to generate additional control propagating pressure waves that interact with those generated by the rotor–stator interaction, with the control parameter being the phase angle between the rotor wake and the speaker–dipole.

## Discrete-Frequency Noise Generation

The model to analyze the discrete-frequency noise generated in a turbomachine considers a rotor and stator in a duct. The flow is described by the convected wave equation, derived by considering compressible, inviscid flow with small unsteady perturbations superimposed. This wave equation is variable separable and harmonic in time, with solution

$$p(\xi, r, \theta, t) = \bar{p}(r)\exp[i(k_\xi \xi + k_\theta \theta - nN_{\text{blades}}\Omega t)] \tag{1}$$

The duct acoustic modes are a result of the unsteady pressures generated by $N_{\text{blades}}$ rotor blades rotating at speed $\Omega$ interacting with $N_{\text{vanes}}$ downstream stationary vanes. Based on periodicity conditions, $k_\theta$ is determined to be

$$k_\theta = nN_{\text{blades}} + mN_{\text{vanes}}, \qquad m = \pm 1, \pm 2, \pm 3, \ldots \tag{2}$$

Thus, the only modes generated by the rotor–stator interaction are specified by these values of $k_\theta$. The frequencies are the harmonics of blade-pass $\omega = nN_{\text{blades}}\Omega$, with the acoustic duct modes also responding at these frequencies.

The linear theory model to analyze rotor–stator interactions considers a two-dimensional flat-plate cascade in a subsonic inviscid isentropic irrotational flowfield. The unsteady flow is considered as a small perturbation superimposed on the uniform mean flow. This gives the linearized continuity and momentum equations. The unsteady flow is harmonic in space and time

$$\begin{bmatrix} u(\xi, \theta, t) \\ v(\xi, \theta, t) \\ p(\xi, \theta, t) \end{bmatrix} = \begin{bmatrix} \bar{u} \\ \bar{v} \\ \bar{p} \end{bmatrix} \exp[i(k_\xi \xi + k_\theta \theta - \omega t)] \tag{3}$$

where the discrete-frequency acoustic waves are defined by $\bar{p}$.

Substitution of Eq. (3) into the linearized continuity and momentum equations results in a system of homogeneous algebraic equations. For a nontrivial solution, the determinant of the coefficients must be zero, leading to the following characteristic equation:

$$(U_\infty k_\xi + V_\infty k_\theta - \omega)[(U_\infty k_\xi + V_\infty k_\theta - \omega)^2 - a_\infty^2(k_\xi^2 + k_\theta^2)] = 0 \tag{4}$$

The solution with $(U_\infty k_\xi + V_\infty k_\theta - \omega)^2 - a_\infty^2(k_\xi^2 + k_\theta^2) = 0$ corresponds to two acoustic waves, one propagating upstream and the other downstream at the speed of sound. The axial wave number $k_\xi$ for these pressure waves is

$$k_\xi = [M_\xi(k_\theta M_\theta - \omega/a_\infty) \pm \sqrt{(k_\theta M_\theta - \omega/a_\infty)^2 - (1 - M_\xi^2)k_\theta^2}]/1 - M_\xi^2 \tag{5}$$

Although all acoustic circumferential modes of order $k_\theta = nN_{\text{blades}} + mN_{\text{vanes}}$ are generated, only some of these modes propagate to the far field. $k_\xi$ specifies whether a mode will propagate or not, specifically the argument under the radical $R = (k_\theta M_\theta - \omega/a_\infty)^2 - (1 - M_\xi^2)k_\theta^2$. When $R > 0$, there are two real distinct axial wave numbers that corresponds to two pressure waves propagating unattenuated, one upstream and the other downstream. If $R < 0$, there are two complex axial wave numbers that correspond to two decaying pressure waves, one upstream and the other downstream. With $R = 0$, there is one wave propagating in the tangential direction.

## Experimental Facility and Instrumentation

The experiments are performed in the Purdue Annular Cascade Research Facility, an open-loop draw-through wind tunnel containing a single turbomachine stage (Fig. 1). The flow, conditioned by a honeycomb section and an acoustically treated inlet plenum, accelerates through a bellmouth inlet to the constant area annular test section that contains a rotor and a stator, with the rotor that serves as a wake generator powered by a 10-hp motor. The flow exiting the test section is diffused into a large acoustically treated exit plenum. The flow is drawn through the facility by a 300-hp centrifugal fan located downstream of the exit plenum. For these experiments, the test section is configured with a 16-bladed rotor upstream of a one- or three-vaned stator. Two types of rotor gust generators are used. Figure 2 shows the excitation produced by the perforated-plate and NACA 0024 airfoil wake generators, where the nondimensional velocity and pressure disturbances are given for all harmonics and the first harmonic only. The freestream absolute, relative, and rotational velocities are $\bar{U}$, $\bar{W}$, and $\Omega\hat{e}_\eta$, respectively. The perforated-plate gust shows the classical characteristics of a vortical gust with negligible pressure disturbance and the velocity disturbance is parallel with the relative flow $\bar{W}$. The NACA 0024 airfoils generate a combined vortical and potential gust, where the velocity and pressure disturbances are of comparable amplitude. In addition, the airfoil gusts are substantially smaller than the perforated-plate gusts.[7]

The rotor rotational speed is 800 rpm, which gives the 16-rotor gust generators a blade-pass frequency of 213.3 Hz. For the one-vaned stator, circumferential modes of order $k_\theta = \ldots, -2, -1, 0, +1, +2, \ldots$ are generated with only the $-2$, $-1$, 0, $+1$, and $+2$ modes propagating. For the three-vaned stator, the circumferential modes of order $k_\theta = \ldots, -5, -2, +1, +4, +7, \ldots$ are generated, with only the $-2$ and $+1$ modes propagating.

Two circumferential arrays of 10 Piezotronics PCB 103A piezoelectric microphones with uniform spacing are mounted via static pressure taps in the outer wall of the inlet annulus. One array is located 22 in. upstream of the stator leading edge,

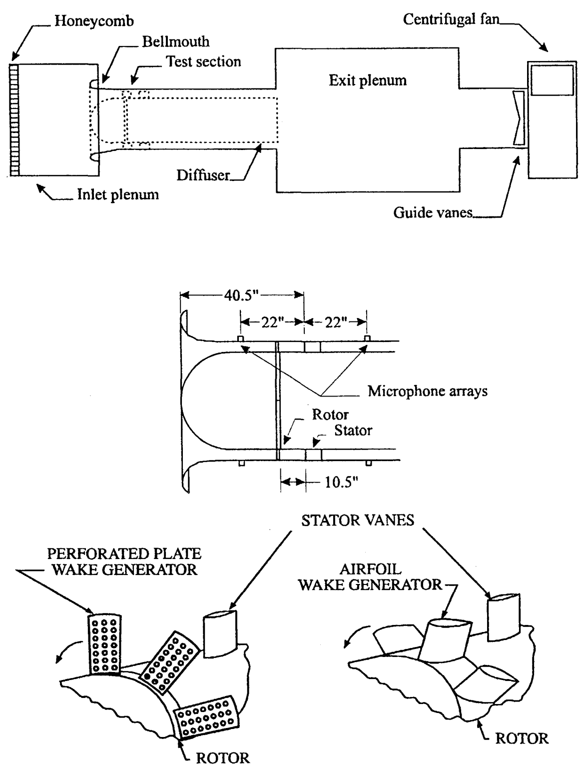


**Fig. 1 Annular cascade facility.**

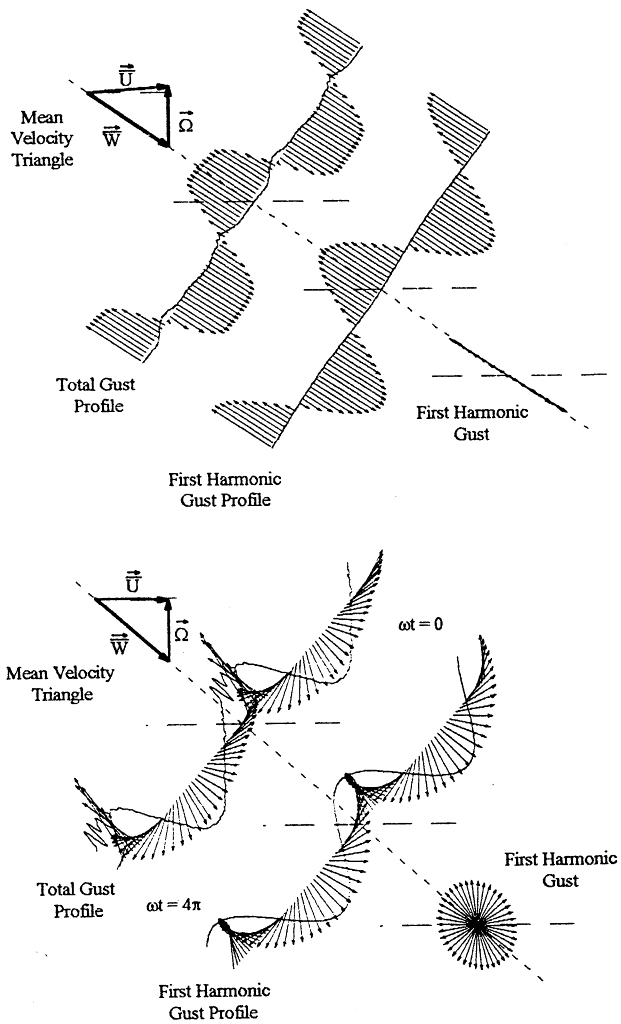


**Fig. 2 Perforated-plate and airfoil rotor-generated convected gusts.**

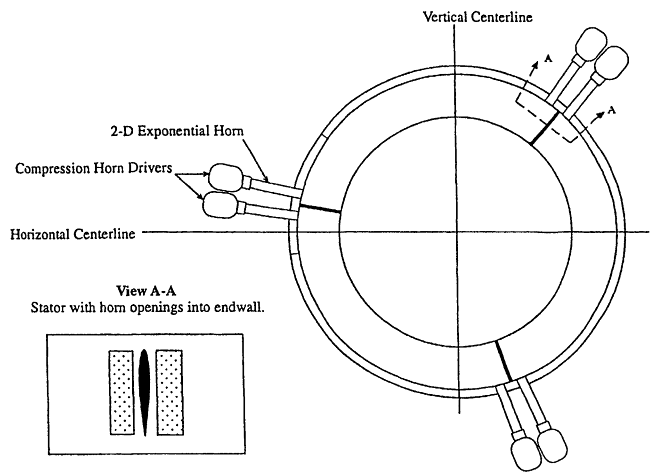


**Fig. 3 Compression driver–dipole configuration.**

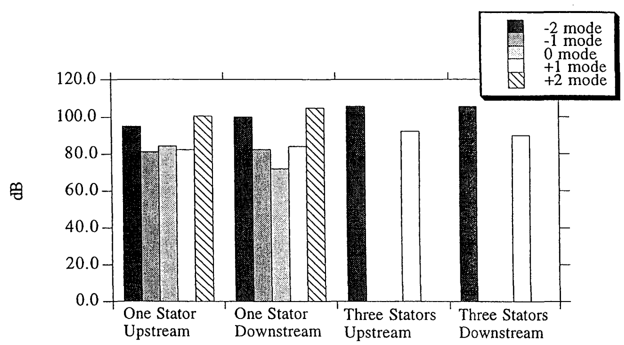


**Fig. 4 Acoustic mode amplitudes at 65 ft/s for perforated-plate rotor excitation.**

and the other 22 in. downstream of the stator leading edge. The microphone signals are digitized at a rate of 250,000 samples/s using three National Instruments NB-A2000 A-D boards with 12-bit resolution installed in a Quadra 950 computer. The data acquisition is triggered with a rotor-based optical encoder signal, with the data ensemble averaged over 400 rotor revolutions. The amplitude of the acoustic pressure is determined within 3% (0.3 dB). The spatial transform of this amplitude modulated signal yields the acoustic mode magnitudes of the pressure patterns rotating in the annulus.[8] Note that the upstream and downstream data are not taken simultaneously.

## Noise-Control Technique

Active noise control is accomplished using a speaker–dipole arrangement (Fig. 3). Surrounding each stator are two compression drivers mounted to exponential horns. The control acoustic waves at blade-pass frequency are enhanced with exponential horns designed for a cutoff frequency of 130 Hz, well below blade-pass frequency (213 Hz). The horns open to the cascade endwall, with perforated plates having an open area of 30%. This allows the efficient transmission of the control sound. The signal to the drivers is a sine wave with the same frequency as blade pass, the drivers being 180-deg out of phase with one another. An optical sensor on the rotor produces a square-wave trigger signal at blade-pass frequency that serves as the input signal to the drivers and provides the timing for the data acquisition. The phase at which the speakers are driven is defined as the gust–speaker phase.

## Results

Figure 4 summarizes the mode amplitudes for the 16 perforated-plate wake generators and the one- and three-airfoil stator vane row configurations at 65 ft/s freestream velocity. Note that the amplitudes of the upstream- and downstream-propagating modes are very close. With one stator, the $\pm 2$, 0, $\pm 1$ modes upstream-propagating acoustic waves are generated as predicted, with the $+2$ and $-2$ modes dominant. With three-stator vanes, only the $-2$ and $+1$ modes propagate, with the $-2$ mode larger than the $+1$ mode. The evanescent modes ($-5$, $\pm 4$, and $\pm 3$) and the propagating modes not generated by the rotor–stator interaction ($-1$, 0, and $+2$ for the three-stator case) have negligible amplitude and therefore are not of interest in this study.

A speaker–dipole system is used to cancel the propagating acoustic modes. The noise change is evaluated by dividing the measured sound-pressure magnitude with the speaker–dipole by the noise measured with no speaker–dipole, $\Delta dB = 20 \log_{10}(P_{controlled}/P_{ref})$.

## Single-Stator Active Control Experiments

A series of active noise-control experiments were performed with the 16 perforated-plate rotor wake generators and the single-airfoil stator vane row. The amplitude of the upstream-propagating $-2$ mode resulting from the active control is presented in Fig. 5. As the gust–speaker phase is varied for a constant speaker power input, the control source affects the noise both constructively and destructively, i.e., if the gust–speaker phase is equal to the phase of the noise source, the resulting mode amplitude is increased, whereas if the gust–speaker phase is 180 deg from the noise source, the resulting mode amplitude is decreased. As the speaker power input is varied for a constant gust–speaker phase, the noise-control effectiveness is altered, with total cancellation occurring at a control-source amplitude equal to that of the noise source. At the 146-deg gust–speaker phase and 5.76 W (rms) power input to each of the two speakers, a decrease of 40 dB is achieved. This corresponds to total cancellation of the −2 upstream-propagating acoustic mode within the sensitivity of the PCB microphones. The largest noise decrease occurs at approximately the same gust–speaker phase for each of the speaker power input levels. This simplifies the control technique so that only one sweep of the gust–speaker phase range and one sweep of the amplitude range are needed to find the conditions for greatest noise attenuation.

Figure 6 shows the influence of active control on the propagating acoustic modes generated by the rotor–stator interaction. The minimum acoustic response is produced when the active control is 180-deg out of phase with the rotor–stator interaction noise. The −2, −1, +1, and +2 modes are reduced from their uncontrolled levels by 36.5, 13, 4.6, and 11.9 dB, respectively. Reinforcement of the propagating spatial modes is exhibited when the active control is in phase with the rotor–stator interaction noise. Similar trends are seen for the downstream-propagating spatial modes, where the active control system reduced the −2, −1, +1, and +2 modes by 17.4, 20.3, 14.9, and 11.9 dB, respectively. Notice that the ±1 modes are 12–20 dB smaller than the ±2 modes. Although the modes are separated herein, the tonal noise perceived is a combination of all propagating modes. Thus, the ±1 modes will not be a concern until the ±2 modes are attenuated near the levels of the ±1 modes.

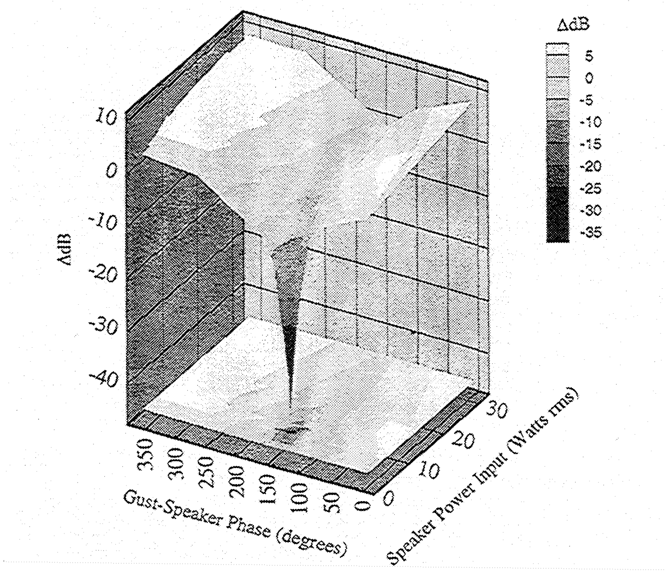


**Fig. 5 Cancellation of upstream-propagating −2 mode, 65 ft/s, perforated-plate rotor excitation.**

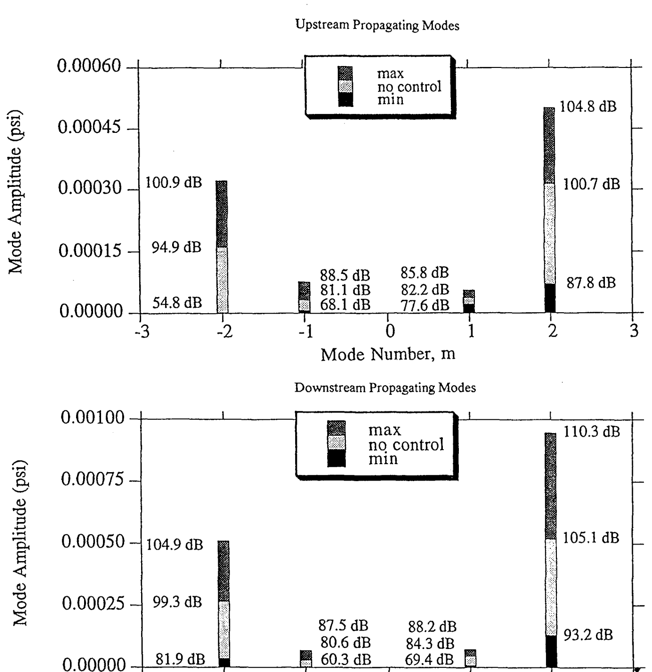


**Fig. 6 Summary of cancellation of upstream and downstream-propagating modes, 65 ft/s, perforated-plate rotor excitation.**

### Freestream Velocity Effects

The effect of freestream velocity was also investigated. For a constant blade-pass frequency (213 Hz) and freestream velocities of 75, 100, and 125 ft/s, the maximum discrete-frequency noise control occurs at a speaker power input of 33 W rms. Figure 7 shows the influence of active control on the −2 spatial mode. Using the perforated-plate wake generators in 75, 100, and 125 ft/s freestream flow, the −2 spatial mode was reduced from the uncontrolled level by 40.1, 8.9, and 3.3 dB at freestream velocity, respectively. To show the effectiveness of this noise-control technique at higher freestream velocities, the perforated-plate wake generators were replaced by NACA 0024 airfoils. The disturbance created by the airfoils is much smaller than that of the perforated-plate wake generators. Thus, the acoustic mode amplitudes are smaller and greater control technique effectiveness is possible at a freestream velocity of 180 ft/s, where the −2 mode was reduced by 9.5 dB.

### Monopole Configuration

The effect of an acoustic monopole, i.e., one speaker, on the propagating acoustic modes is also considered (Fig. 8) for a blade-pass frequency of 213 Hz and a freestream velocity of 68 ft/s. For the monopole and dipole control of the upstream-propagating ±2 modes, at 45-deg phase, the +2 mode is at a minimum (−8.3 dB) and the −2 mode is at a maximum (8.5 dB). The −2 mode is reinforced by the single speaker, with the largest decrease being 1.0 dB at 270-deg of phase. Using a dipole, the largest noise decrease for the two modes occurs at the same phase. With the dipole, the −2 mode results in a maximum noise decrease of 13.7 dB and an increase of 7.7 dB, whereas the +2 mode has a maximum noise decrease of 12.8 dB and an increase of 7.2 dB.

Comparing the dipole and monopole results shows that the dipole simultaneously minimizes the +2 and −2 modes, whereas the monopole results in a decrease in one mode but an increase in the other. This suggests that the speaker on one side of the airfoil cancels the noise created on that side of the airfoil but reinforces the source on the opposite side of the airfoil. Because the ±2 modes are of approximate equal amplitude, a noise decrease would not be perceived if only one of the modes is decreased. Similar results were obtained for the monopole and dipole control of the downstream-propagating ±2 modes. Hence, the dipole speaker arrangement has a

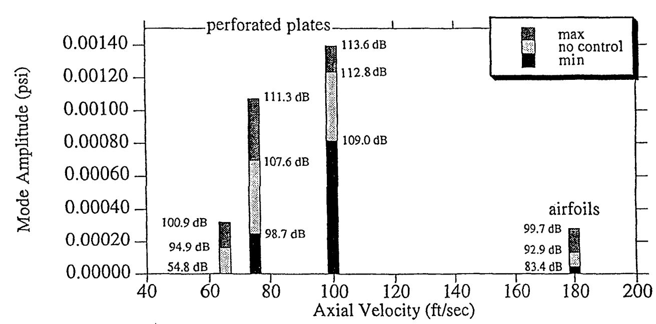


**Fig. 7 Mode amplitude comparison for upstream-propagating −2 mode, perforated-plate, and airfoil rotor excitation.**

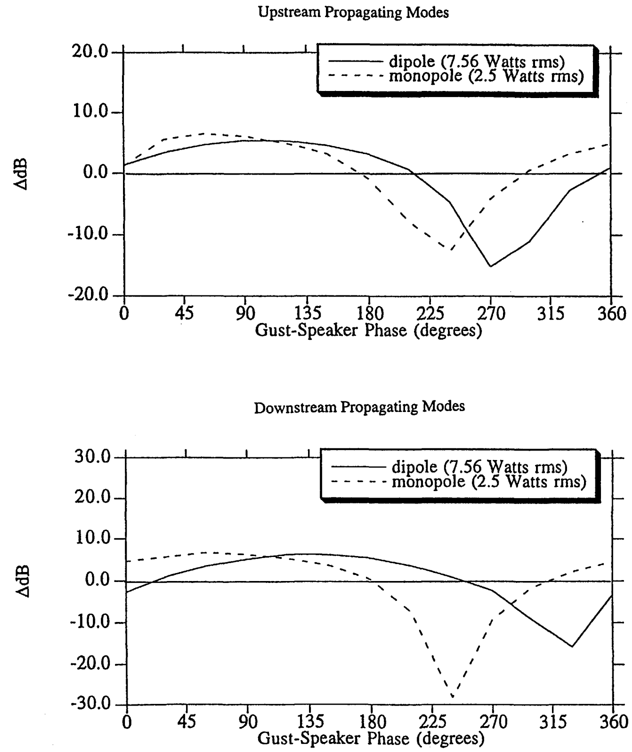


**Fig. 8 Monopole and dipole active control of ±2 mode 68 ft/s, 5.76 W rms speaker power input, perforated-plate rotor excitation.**

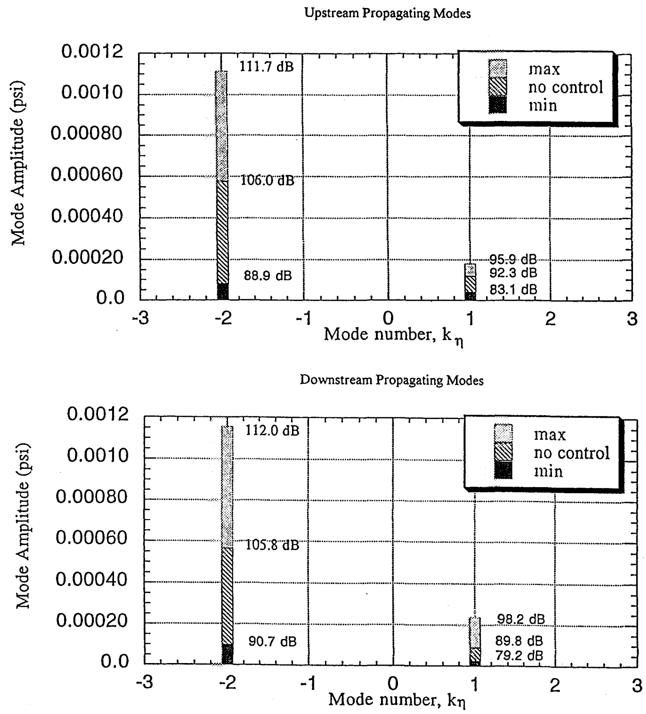


**Fig. 9 Summary of control of upstream and downstream-propagating modes 65 ft/s, 7.56 W rms speaker power input, perforated-plate rotor excitation.**

greater noise decrease than the monopole, and the +2 and the −2 modes are decreased simultaneously, whereas the monopole attenuates one mode while reinforcing the other.

## Three-Stator Active Control Experiments

The −2 and +1 modes propagate, with data taken with the perforated-plate wake generators at a freestream velocity of 65 ft/s and a reduced frequency of 1.64, where the 16-bladed rotor interacts with the three-vaned stator. Sweeping the speaker power input, the maximum mode control was found to occur at 7.56 W rms speaker power input.

Figure 9 shows the effectiveness of the active noise-control system on the upstream- and downstream-propagating −2 and +1 modes. For the upstream-propagating modes, the −2 mode was controlled to achieve a 17.1 dB maximum decrease with a 5.7 dB maximum increase from the uncontrolled value of 106.0 dB. The +1 mode resulted in a decrease of 7.2 dB and an increase of 3.6 dB with respect to the uncontrolled value of 92.3 dB. For the downstream-propagating modes, the −2 mode was decreased by up to 15.0 dB and increased by as much as 6.2 dB, whereas the +1 mode was decreased by up to 9 dB and increased by as much as 7 dB. Overall, the +1 mode is 13.7–20 dB smaller than the −2 modes. As in the single-stator case, the +1 mode will not be significant until the −2 mode is attenuated to the level of the +1 mode because the total noise is the combination of the modes.

### Monopole Configuration

One speaker was powered for each stator to create a monopole on one side of each stator. The results for the −2 mode are shown in Fig. 10. The upstream-propagating −2 mode is attenuated 15.3 dB with the monopole and 12.6 dB with the dipole. The downstream-propagating −2 mode is attenuated 28.1 dB by the monopole and 15.7 dB with the dipole. Note that only 2.5-W (rms) power input to the speaker is required for the monopole and 7.56 W (rms) is required for the dipole for the best noise control, as determined experimentally.

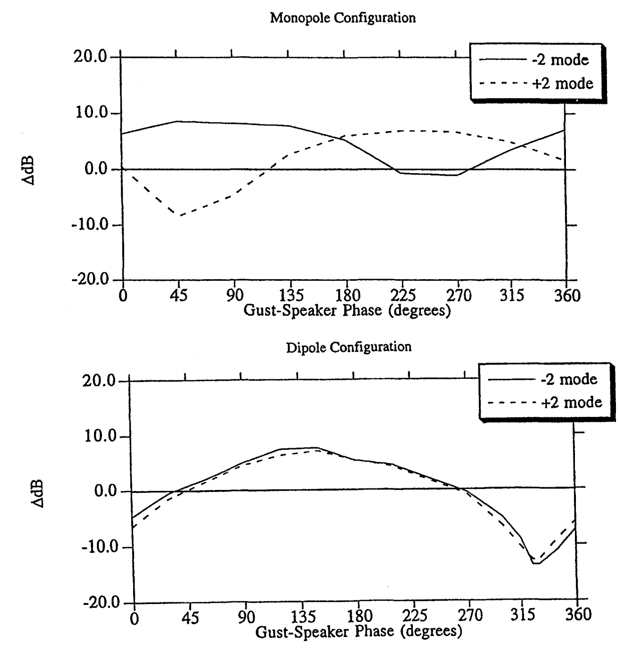


**Fig. 10 Monopole and dipole active control of −2 mode, 65 ft/s, perforated-plate rotor excitation.**

To evaluate the performance of the monopole compared with the dipole, the overall noise levels of each of the modes and the phase at which the modes are attenuated must be considered. Figure 11 shows the amplitude levels of the upstream- and downstream-propagating −2 and +1 modes for the dipole and the monopole configurations at the gust–speaker phase in which a minimum −2 mode amplitude is achieved. For the upstream-propagating modes, the monopole control source creates a +1 mode of 100.0 dB that is higher than the −2 mode (92.9 dB controlled and 106 dB uncontrolled). Although the controlled +1 mode is higher than the minimized −2 mode, there is still a net decrease in the combined tone from the uncontrolled three-stator case. The dipole results in a 90.8-dB upstream-propagating +1 mode, with the −2 mode reduced to 88.9 dB. The +1 mode is only slightly above the controlled −2 mode for the dipole configuration.

For the downstream-propagating modes, the monopole control source yields a +1 mode of 99.0 dB and a −2 mode of 77.9 dB. The uncontrolled −2 mode is 106.2 dB. As in the case of the upstream-propagating modes, the +1 mode is increased above the level of the minimized −2 mode, but substantial attenuation of the overall tone is achieved. The +1 mode generated with the dipole configuration is 84.1 dB, which is smaller than the 90.7 dB amplitude of the −2 mode.

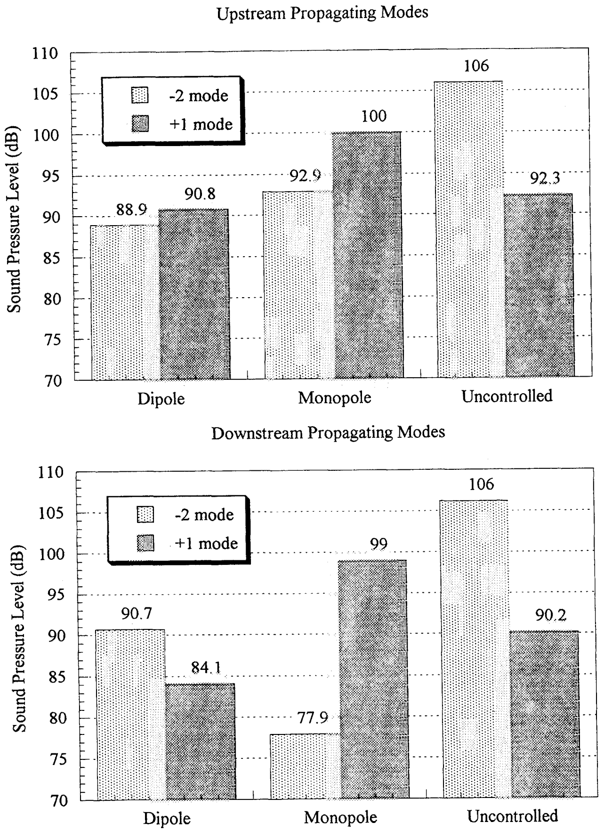


**Fig. 11 Monopole and dipole control of upstream- and downstream-propagating −2 and +1 modes at gust-speaker phase for minimum −2 modes, perforated-plate rotor excitation.**

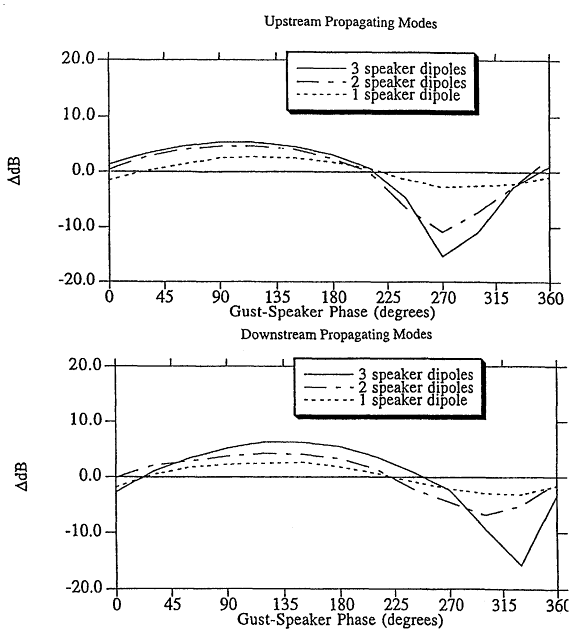


**Fig. 12 Control of upstream- and downstream-propagating −2 mode using 1, 2, and 3 speaker dipoles, perforated-plate rotor excitation.**

For the three-stator case, the monopole performs slightly worse than the dipole, but it is still a viable noise-control technique. Furthermore, the monopole control source may be a more desirable configuration because half the number of control sources are utilized and less power input to the speakers is required. Generally, the monopole is more efficient than the dipole because the dipole has inherent cancellation within itself.

### Number of Speaker Dipoles

The number of speaker dipoles utilized in the three-stator case was varied to determine if a minimal number of speakers could be used. The results for the −2 mode are given in Fig. 12. The use of three dipoles results in the greatest noise control (−15 dB upstream and −15.7 dB downstream), although two speaker dipoles produce substantial noise reduction (−11 dB upstream and −6.8 dB downstream). Using only one speaker dipole for noise control has much less effect (−3 dB upstream and −3.1 dB downstream) for the upstream-propagating −2 mode.

## Summary and Conclusions

A series of experiments was performed and directed at the active control of discrete-frequency noise generated by subsonic blade rows through cancellation of the blade-row interaction-generated propagating acoustic waves using a speaker–dipole system. The active control of the propagating acoustic modes generated by 16 rotor blades interacted with one- and three-airfoil stator vane rows.

In the one-airfoil stator vane row, the −2, −1, 0, + 1, +2 modes were shown to propagate, as predicted, with the −2 and +2 modes dominant. Complete cancellation of the −2 mode was achieved, with simultaneous attenuation of all the propagating modes both upstream and downstream. Thus, the overall tone created by the propagating acoustic modes was attenuated. An increase in freestream velocity caused the mode strengths to increase and the noise-control effectiveness to decrease. This was shown to be because of poor amplitude matching of the control source with the noise source and not the increase in speed.

The three-stator configuration generated −2 and +1 propagating acoustic modes, with the −2 mode dominant. Mode cancellation was achieved and all of the upstream- and downstream-propagating modes were simultaneously attenuated. The number of speaker dipoles utilized was also varied. The use of three speaker dipoles resulted in the optimal noise-control system, but the one- and two-dipole systems were also effective. A typical turbomachine would have more than three stators, and the requirement of two speakers per stator may be too burdensome in terms of weight and complexity of the noise-control system. Decreasing the number of control sources utilized may be a worthwhile compromise.

The effectiveness of a monopole configuration was examined for both the single- and three-stator configurations. The three-stator monopole configuration was found to be effective, whereas the single stator was not. For the single stator, the −2 mode was minimized, resulting in a reinforced +2 mode. For the three-stator monopole configuration, the −2 mode was attenuated while the +1 mode was reinforced. However, the +1 mode was still substantially smaller than the uncontrolled −2 mode, thereby resulting in overall abatement of the discrete-frequency tone. Furthermore, the monopole configuration required less speaker power input than the dipole. Thus, although it results in less noise attenuation, the monopole configuration may well be the better of the two noise-control techniques.

## Acknowledgments

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