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Adjoint-based optimal control methods are used to study the mechanics of jet noise. One objective is to establish the upper limit for noise control effectiveness given a set of physical contraints. A second objective is to generate noisey and quieted versions of the same flow which can then be compared to identify the mechanisms leading to noise reduction. The talk will discuss in detail results for a two-dimensional mixing layer, which was studied as a model for the near-nozzle region of a jet. It is shown that a substantial noise reduction is possible despite the fact that the flow itself is barely changed by the control.

REDUCTION of jet noise remains an elusive control objective. Certain nozzle geometry modifications are known to reduce noise,[1] and some of these even have acceptable losses.[2] Unfortunately, because of the lack of quantitative predictive tools for jet noise, their design always entails some degree of trail-and-error interations. Thus, it is never known if any sort of optimum has been reached in their design. Presumably, if there were a quick and reliable means of predicting jet noise, control theory could be applied to optimize nozzle geometry with less need for expensive experiments. It would also be easier to investigate active control of jet noise.

It is the nature of jet noise, and aerodynamic sound generation in general, that causes the difficulty. Even for the apparently loud near-sonic jets on civilian aircraft, the noise accounts for only a minuscule fraction of the flow's energy ($\lesssim 10^{-3}$). There is currently not even a phenomenological model for coupling the turbulence to its noise.

In a sense, the radiated acoustic energy comes from individual noise sources that do not quite completely cancel one another, letting only a small amount of energy leak into the far field as sound. In the zero Mach number limit, which has been used successfully in jets, these source are quadruples,[3] so at finite subsonic Mach numbers the sources are often said to have a quadrupole character. A related characterization is that individual turbulent structure do not directly radiate because their wavenumber-frequency makeup is such that they can only spawn evanescent pressure waves. It is a subtle aspect of the growth and decay of turbulence structures, or their mutual interactions, that puts energy in components with radiation capable phase velocities. In light of this, it is not surprising that expressions relating near-field turbulence statistics to acoustic radiation are complicated and have not lead to a completely satisfactory prediction capability.

Faced of the complexity of the aeroacoustics of free shear flows, jet noise in particular, we have developed and applied an optimal control methodology. Since trail-and-error experiments have shown modest reduction in noise, we want to determine what the the upper limit of this reduction might be: How quiet can a flow be made given a particular set of physical constraints? We focus on active controls since their generality should make them more effective than passive controls. Another question concerns the relative effectiveness of different types of actuation. Any actuation is a combination of mass, momentum, and energy sources. Of these, it is not clear what type or types of actuations will be most effective for noise reduction. Of course, practical consideration will need to be included for any actual actuator design but the relative effectiveness of different types of actuation should also be accounted for, which is not currently possible because it is unknown.

Once a flow has been quieted, as it can be with the algorithm we developed, two further questions arise. The first concerns whether or not the noise reduction can be accomplished by small perturbations so the control would be energy efficient. The second question simply asks what changed? That is, can an effective control mechanism be deduced by comparing the flow before and after it is controlled? To answer these questions, we need a method that circumvents the complexity of the processes and automatically identifies effective controls. We note, however, that since we are primarily interested in studying the mechanics of sound generation, we are not yet concerned with the practical aspects of hardware implementation, though practical constraints can be designed into our meth-

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ods.

A conjugate gradient search algorithm is used to optimize our controls, with the gradient direction determined by a numerical solution of the adjoint of the compressible flow equations, as was done for the control of wall bounded incompressible turbulence by Bewley *et al.*[4] The algorithm proceeds as follows. The flow and its noise are first solved numerically without modeling approximations. Then the adjoint of the compressible flow equations, which is formulated with a forcing term based on an appropriate metric of the noise, is solved numerically backward in time. This adjoint solution provides the sensitivity of the noise to changes in control near the nozzle, allowing the control to be updated accordingly. Finally, the procedure is repeated until a criterion for minimum is satisfied. This is shown in figure 1, which is a schematic of the model two-dimensional mixing layer that we have studied. Control is applied in the small labeled region near the inflow boundary, and appears as a general source term in the governing equations. Each space-time point of the discrete representation of this control term is treated as a distinct control parameter to be optimized. For these simulations, there are typically over ten million control parameters thus optimized, which necessitated the adjoint based approach.

It should be clear that this algorithm is not designed as a practical control approach. Instead, it is used as a diagnostic for studying noise mechanisms. The adjoint solution depends upon full flow field information that is only currently available in a direct numerical simulation[5] or large-eddy simulation.[6] Furthermore, the adjoint solution is as computationally challenging and expensive as the flow solution, so it clearly can not be implemented in real time in an application. Furthermore, the actuation we are optimizing in these efforts is more general than can probably be realized in hardware. For now, we seek the best that can be done assuming this most general actuation.

The talk will discuss results from our two-dimensional mixing layer simulations. The high-speed stream has Mach number 0.9, which models the jet's core flow, and the low-speed stream has Mach number 0.2. The temperature is uniform at the inflow boundary. The actuation function has support only in the small box region shown in figure 1. The control objective is the minimization of the mean square acoustic pressure on the line Ω shown in the figure.

We find that the optimal control reduces this noise metric by over a factor of five in some cases, which is over 7 dB. We also find that a temperature control is somewhat more effective than a unidirectional momentum control. In all cases, the flow is changed little by the actuation, which is encouraging because it suggests that only a small amount of energy might be required to accomplish the noise reduction. The mean flow development, the turbulence kinetic energy, and the

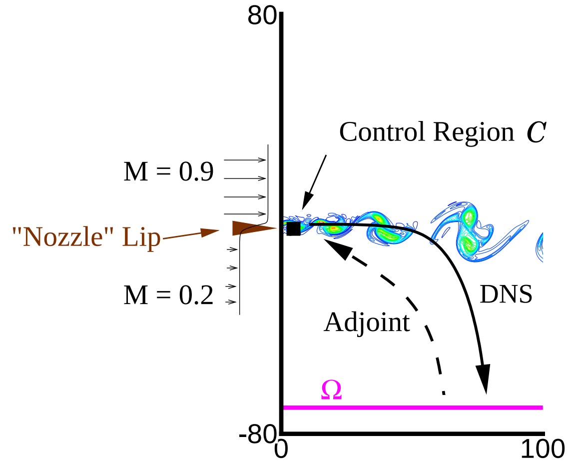

Fig. 1 Mixing layer control schematic. The line Ω is the support of the noise metric to be minimized. The small black box $\mathcal{C}$ near the "nozzle" lip shows the support of the control. Arrows indicate the DNS solution (forward in time) and the adjoint solution (backward in time), which provide the sensitivity data.

qualitative evolution of the large-scale unsteady flow structures are all nearly identical before and after the application of the control. More detailed results are reported elsewhere[7,8] and are therefore not repeated here. These results will be discussed in full detail in the presentation.

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