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ACTIVELY CONTROLLED TRANSVERSE GAS INJECTION

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In general the problem of feedback control for an unsteady fluid flow is nonlinear. Especially challenging is the control of mixing processes in a hot, potentially reactive environment. Because of the high temperatures present, realistic sensors can only operate mainly in cool regions, e.g., away from flames and hot exhaust regions. Consequently, there is often a large time lag between the time at which an actuator would modify, for example, a fuel or dilution air jet's characteristics in a combustion chamber, and the time at which a sensor would measure the effect of this action on the jet's mixing and/or reaction processes. During this time lag, flow dynamics, mixing, and combustion chemistry, if present, are dominated by nonlinear effects [1].

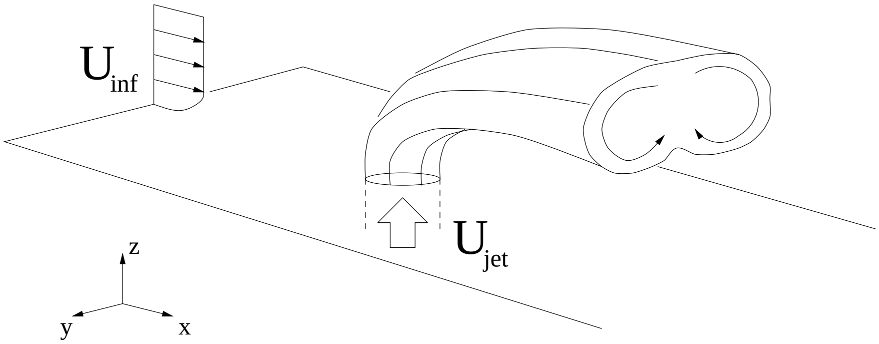


Figure 1: Flow geometry for a steady jet of bulk velocity $\mathrm{U_{jet}}$ in a crossflow with freestream velocity $\mathrm{U_\infty}$. Global development of the CVP is shown.

One of the challenging aspects of controlling such mixing processes is that there are usually both fast and slow characteristic time-scales present. In the presence of a combustion reaction, there will be additional reaction time scales that couple to the fluid mechanical time scales. Consider, for example, the canonical flowfield of the non-reactive jet in crossflow, or transverse jet, as shown in Figure 1. In this flowfield there is a "fast" time-scale T_f over which the Kelvin-Helmholtz instability induces the formation of (secondary) vortex ring structures, but there is also a "slow" time-scale T_s over which the evolution of these vortical structures affects the mean properties of the flow. A striking feature of the mean flow of the transverse jet is the counterotating-vortex-pair (CVP), shown in Figure 1, which is observed to be associated with the jet cross-section. This vortical structure exists only in an average sense, since instantaneous measurements of the jet's vorticity field do not always clearly reveal the existence of the CVP. Mean measurements of the flow field suggest that the CVP is responsible for the entrainment of the crossflow into the injectant and, consequently, for the excellent mixing characteristics of the transverse jet as compared with the jet injected into quiescent surroundings.

Active control of the mixing processes associated with the transverse jet (open as well as closed loop) may be accomplished through excitation of the jet flow issuing from the orifice shown in Figure 1. Limited experiments on pulsed or acoustically driven transverse jets [2–4] demonstrate that temporally varying the jet velocity allows jet penetration and spread to be enhanced, at specific conditions of excitation, due to control of the generation of jet vorticity and hence control of the fast time scale T_f. In practice this type of actuation can be achieved for gaseous injectants using a loudspeaker placed in the plenum upstream of the jet orifice, while for liquid injectants the excitation can be achieved using a rotating valve placed within the line which delivers injectant to the orifice. In either case a signal generator may be used to produce the desired temporally varying jet velocity. In reality, however, there is experimental [3, 4] and numerical evidence [5] which suggests that the temporal variation of the velocity $\mathrm{U}_{\mathrm{jet}}$ at the orifice can be quite different from that imposed by the signal generator. Although the dominant frequency of excitation is retained by the jet, differences in actual duty cycle, phase, and waveform shape can arise due to the unsteady flow evolution within the jet plenum and nozzle, as well as due to the jet's nonlinear coupling to the crossflow. Most significantly, the difference between the input function and the resulting temporal jet velocity variation is apparatus-dependent.

A goal of the present study is to develop control strategies to optimize the mixing characteristics associated with the actively driven jet in crossflow. As a consequence of the differences between signal generator input function and jet exit velocity temporal variation (which is the actuation for the flowfield), it becomes necessary to design a feedback controller for the jet actuator, shown in Figure 2, which is distinct from the plant controller used for the overall experiment. Moreover, in developing a controller for the transverse jet problem there is an interesting trade-off between the complexity of actuating and sensing. On the one hand, while the temporal excitation of the jet velocity is clearly a good candidate for manipulating the flow [2–4], there are a number of quantities which could be sensed or measured in order to provide timely feedback information to the

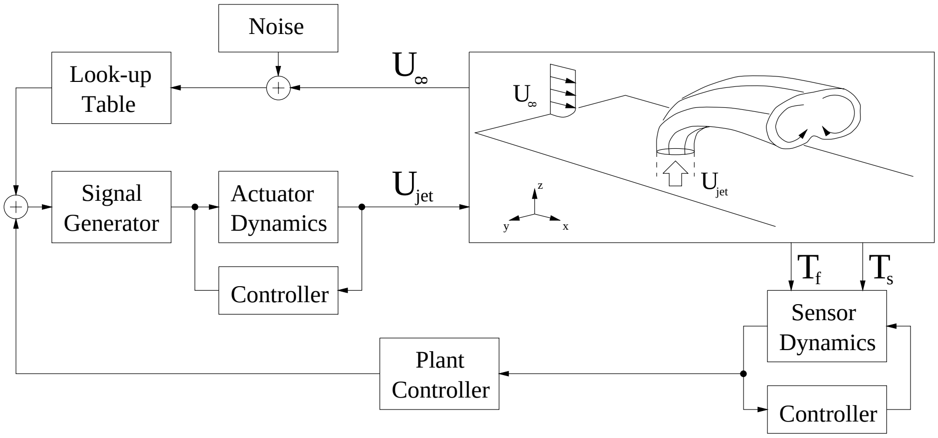


Figure 2: Block diagram of control strategies for the pulsed transverse jet.

controller, quantities which are potentially relevant to mixing and/or combustion efficiency. Further, while actuation is necessarily associated with manipulating the vortical structures generated by the jet on fast time scales T_f, there is the possibility of distributing different sensors which can measure quantities evolving on both fast and slow time scales (e.g., pressure and temperature, respectively). Hence in designing a control algorithm for this problem, as shown in Figure 2, "Sensor Dynamics" could represent a sophisticated mixture of sensors (pressure, temperature, species, flame luminosity, etc.) which may be used to extract information about flow properties evolving on both time scales. Sensing thus also becomes a separate control problem in itself, requiring a separate controller because sensors operate under extreme conditions and must be capable of self-testing and self-calibration. Finally, while the plant controller may be developed once actuator and sensor dynamics are characterized, uncertainties in the input variables such as crossflow velocity U_∞ must be characterized and included in the control strategy as well, although an appropriate assumption which can be made is that the crossflow velocity is quasi-stationary over a time scale of the order of the slow scale, T_s.

In order to create a useful framework for developing a robust feedback controller for this problem, we form a preliminary controller with a feed-forward loop, based on a look-up table, as described in the block-diagram shown in Figure 2. This architecture has been selected to allow for the parallel effort of: 1) modeling the mean effect of the vortical structures on the mixing characteristics of the transverse jet, and 2) developing a feasible controller based on actuator dynamics. The look-up table is constructed by searching the parameter space for the combination of quantities that produce optimal mixing for given crossflow conditions. The input to the look-up table is the crossflow velocity U_∞, and the output parameters for the jet are the settings for the signal generator which modulate the jet velocity $\mathrm{U}_{\mathrm{jet}}$. The measurement of the crossflow velocity could also provide information about the background level of turbulence or the type of boundary layer formed upstream of the jet, yet this information could also be classified as contributing to uncertainties. The uncertainties are represented by the block "Noise" in Figure 2. The look-up table should be viewed from the perspective of a block that could be replaced by a neural network or by a genetic algorithm which could provide more accurate input settings for the wave generator.

A feed-forward loop based on a look-up table does not use any information about the flow processes affected by the action of the actuator and consequently relies only on the accuracy of the look-up table. Accurate data, in terms of the relationships among measured flow variables, actuator dynamics (jet responses to imposed excitation), and sensor dynamics are therefore needed in this feed-forward control approach. In the present study, the actuator and sensor dynamics are characterized for the look-up table by two alternative, comparable means: 1) through gas-phase experimental studies, and 2) through 3D transient numerical simulations.

The present gas phase experiments are conducted in a blow-down wind tunnel in which a round air jet, seeded with smoke, is introduced perpendicularly into a crossflow of air [4]. Quartz windows are fitted in two perpendicular side walls of the test section and at the downstream end of the wind tunnel (in a plane perpendicular to the bulk flow) for optical access. Acoustic excitation of the jet is accomplished by placement of a loudspeaker (subwoofer) at the bottom of the jet plenum, which is driven by a function generator and amplifier. Sinusoidal as well as square wave excitation can be imposed for a wide range of frequencies, amplitudes of excitation, and duty cycles. The functional form of the variable speaker voltage thus becomes the input to the "actuator dynamics" block in Figure 2. The temporal response of the jet to such actuation, through its exit plane velocity $\mathrm{U}_{\mathrm{jet}}$, is quantified via hot wire anemometry. Hence the input-output relationships which characterize the actuator dynamics in the experiments may be quantified and used to design a feedback controller or shaping filter with the objective of gaining more authority over the temporal shape of the jet velocity. An example of input-output (jet velocity-speaker voltage) data, for different frequencies of excitation, is shown in Figure 3. Sensed information in the experiments at present consists of measures of jet penetration and vertical spread, as visualized using smoke injection in the jet. Sample smoke visualization images, for unforced and forced gas jets, are shown in Figure 4.

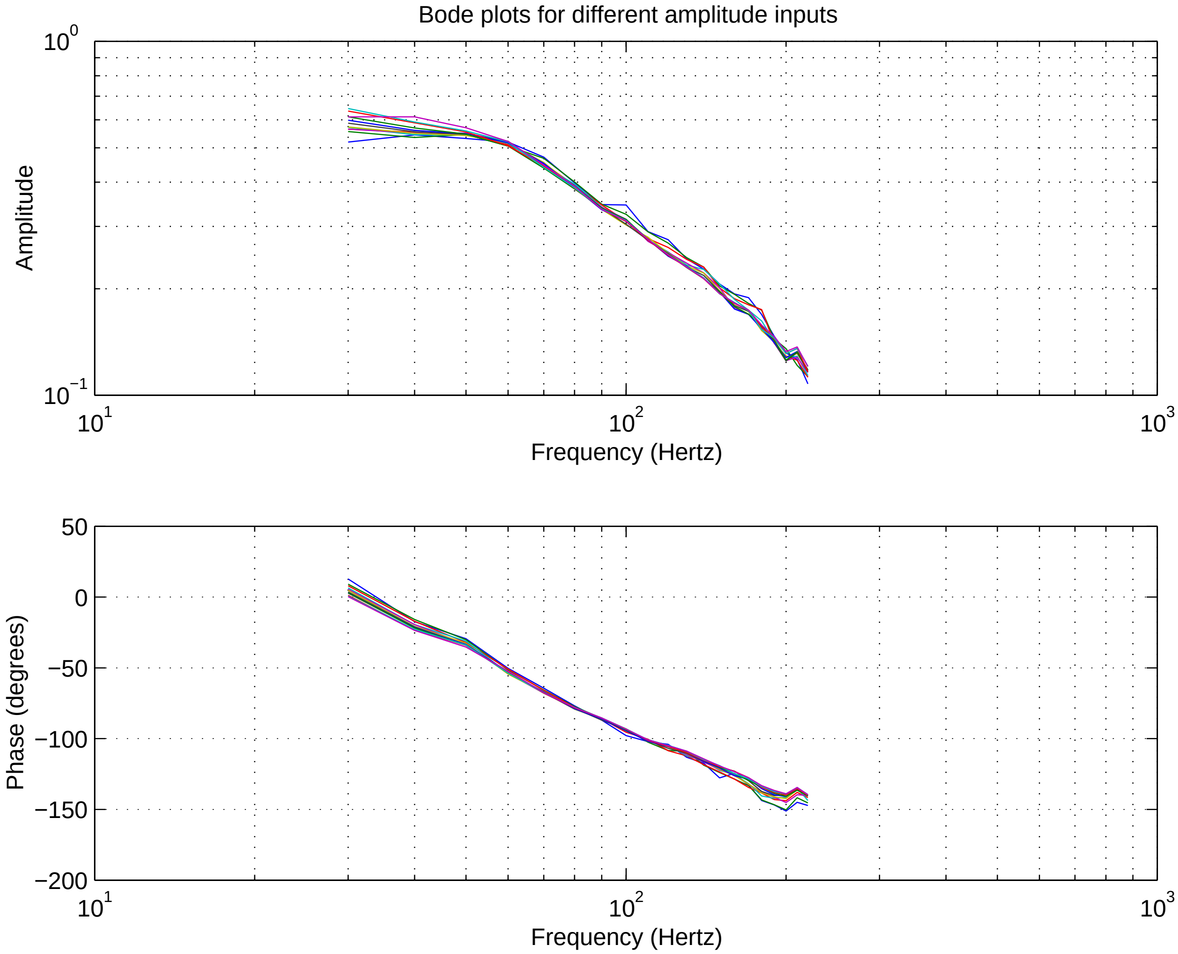
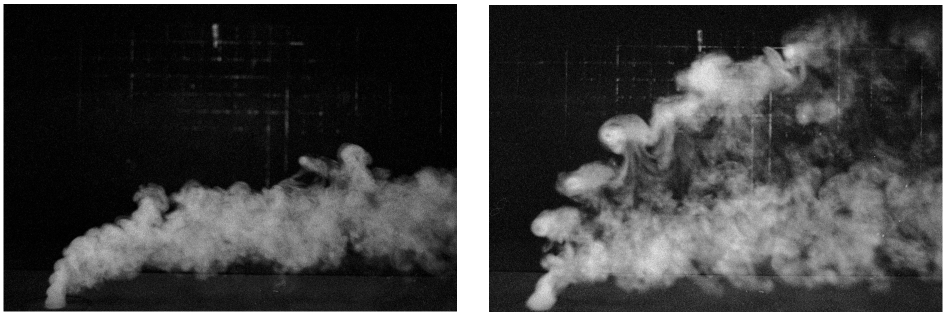


Figure 3: Sample Bode plots of magnitude and phase for the jet exit velocity response to speaker input for the pulsed transverse jet. Results shown are for a range of amplitudes of speaker input excitation.

A complementary approach using three-dimensional vortex filament simulations of the actively forced transverse jet [5–7] is also used to investigate actuator and sensor dynamics and the mechanisms for mixing enhancement that occur in the jets. These simulations represent the mean jet flow using a semi-infinite, cylindrical vortex sheet, where the jet velocity is a function of the circulation per unit length of the vortex sheet. In general the jet velocity can be expressed as $\mathrm{U_{jet}} = \bar{\mathrm{U}}_\mathrm{j} + \mathrm{a_j f}(2\pi\omega \mathrm{t})$, where $\bar{\mathrm{U}}_\mathrm{j}$ is a constant mean velocity and $\mathrm{a_j}$ is the amplitude of forcing at frequency ω. Different functional forms of f for jet forcing are currently being explored. The jet



(a) (b)

Figure 4: Smoke visualization of the jet in crossflow at an average velocity ratio of $\bar{\mathrm{U}}_\mathrm{j}/\mathrm{U}_\infty = 2$: (a) unforced jet operation, and (b) square wave jet excitation with frequency 80 Hz and duty cycle 30%.

shear layer is modeled by introducing a 3D vortex filament or ring near the jet exit at each time step of the computation. The velocity field induced by the evolution of the vortex filaments is then computed from the modified Biot-Savart integral. Parametric studies of the jet in crossflow, with and without jet pulsation [5], show that the most critical parameters to be modified include the mean jet-to-crossflow velocity ratio, the upstream boundary layer thickness, the jet pulsation frequency, its forcing amplitude, and the "duty cycle" of the oscillations (for square wave excitation). In the computations, the input to the "actuator dynamics" block in Figure 2 is the theoretical input velocity within the pipe that would generate a vortex sheet of the desired exit velocity profile. The temporal response of the jet to such actuation, through its exit plane velocity U_jet, is quantified by post-processing the evolved velocity field after the transverse jet has reached its limit cycle behavior. Hence the input-output relationships which characterize the actuator dynamics in the computations may be quantified and used in the look-up table, in a similar manner to that done in the experiments. Sensed information in the computations consists not only of measures of jet penetration and vertical spread, but also of jet mixedness, as described below. Sample results of the 3D simulations, for the pulsed jet in crossflow, are shown in Figure 5.

This 3D simulation allows us to characterize mixing processes by implementing numerically a technique similar to that of passive particle tracking, often used experimentally. The tracking of passive (massless) fluid particles is computed efficiently by a Lagrangian scheme such as the present vortex code. The degree of mixedness associated with particle concentrations in different cross-sectional slices of the jet flowfield can be determined and compared with mixing characterizations as obtained by corresponding gas phase experiments. Mixedness as well may be used to characterize sensor dynamics. Global quantities such as the mixing length of the jet can also be obtained from these simulations. Hence the optimal conditions for augmented jet mixing may be predicted by the current high-order model and used in feed-forward control of pulsed transverse jet processes.

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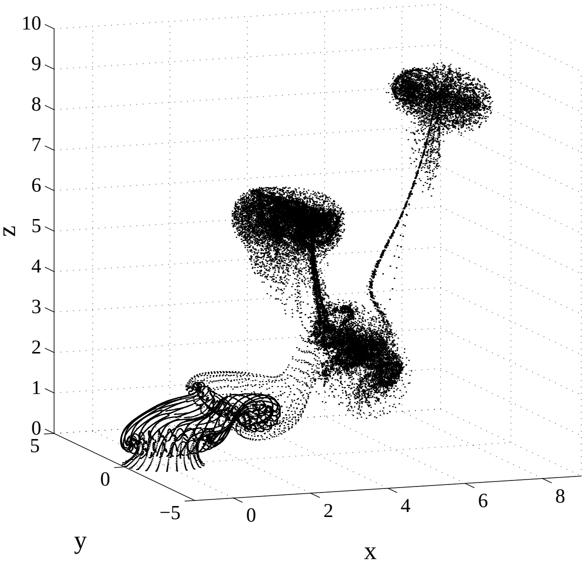

Figure 5: Simulation of 3D vortex structure for the forced jet in crossflow with square wave excitation, $U_j/U_\infty = 2.54$, duty cycle 15%, Strouhal number 0.35 (corresponding to jet frequency 85 Hz in the experiments), at non-dimensional flow time 6.2.

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