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CHARACTERISTICS OF CLOSED-LOOP CONTROL IN AN AXISYMMETRIC JET AT MACH 0.6

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ABSTRACT

A turbulent compressible Mach 0.6 jet was used as a test bed for applying closed loop flow control schemes, with the control objective of increased mixing in the shear layer observed by a change in the far-field noise. The Reynolds number, based on a nozzle exit diameter of 0.0508m, is 690,000. An azimuthal array of eight zero-net mass flux piezo-electric jets, placed at the jet exit, was used for control authority. The actuators were driven at 1900Hz, corresponding to an exit velocity ≈ 50m/s from each actuator. Three control cases were tested, an open loop mode-0 excitation, a closed loop mode-0 (*column mode*) excitation, and a closed loop mode-1 (*helical mode*) excitation. A spatial Fourier azimuthal decomposition of the near-field hydrodynamic pressure at 8D in the stream wise is used for state estimation and feedback. The far-field sound was measured with six microphones oriented along a boom at increasing polar angles from φ= 15°-90° at 75D downstream to evaluate the effectiveness of each controlled case. For φ = 15° (shallow angle), an overall increase in the sound at lower Strouhal numbers (0.04 – 0.2) of the jet was noticed for all controlled cases. The greatest reduction was noticed for the closed loop mode-0 case. Conversely, an overall decrease in the sound was noticed at higher jet Strouhal numbers (0.2 – 3.7). At φ = 60° and 90°, there was an overall increase in far-field sound for all controlled cases.

INTRODUCTION

It is evident that the future of the aviation industry is driven by new generation technology and intelligent systems. The pilots of today are relying more and more on on-board and off-board computers for "everything from aircraft control and navigation to weapons guidance. The air force of the future will be virtually undetectable. Planes will be super agile, turning and twisting in the air like a bird. Stealth, super cruise, and super maneuverability are the new buzz words at the cutting edge of military aviation" [1].

To date, one of the more challenging and far-reaching aspects of fluid dynamics, remains the prediction and ultimate control of highly turbulent, non-linear, flow physics. It has been seen with direct numerical simulation DNS of Freund *et al.* [2] that free shear flows can be controlled to be made quiet, although, the applications for control of fluid systems are not limited to the reduction of aero-acoustic noise. These techniques have numerous applications, such as increasing turbulent mixing, improved aerodynamics, *i.e.* the reattachment of separated flows, masking wake signature, and reducing the adverse effects of aero-optics, to name a few. Much of this effort lies in developing an understanding of the dynamics in a highly random, turbulent flow field so that technologies developed in the laboratory can be transitioned. This understanding is vital in determining which features of the flow a control strategy will manipulate, or what signals to feed back in closed-loop applications. However, it is important to note that while a full understanding of nonlinear dynamics of the jet, which lead to noise generation, is interesting from a fundamental standpoint, it is not necessary in a flow control application [3]. This research is two-fold in this respect, initially aimed at the low-dimensional identification of the turbulent flow structure and subsequently the development of novel, yet feasible in terms of application, control schemes.

CONTROL TECHNIQUES

At the heart of these efforts lies the methodology known as flow control. Flow control can be broken up into two families, passive and active flow control.

Passive flow control is characterized by any modification made to a system that does not input any energy into the system to achieve a desired flow response. The most common passive flow control method for the jet includes geometric modifications such as tabs or chevrons. Although both serve to increase mixing and help to mitigate the noise signature, they ultimately reduce overall thrust [4].

Active flow control is characterized by a control strategy that utilizes energy input to generate a control signal such as open and closed loop control.

Figure 1. Open Loop Control

Open loop active flow control techniques have been seen to have sufficient control authority to affect the jet flow. Using an array of plasma actuators mounted around the periphery of the jet and run at a constant signal, it has been shown by Samimy et al. [5] that the structure of the flow and the noise production was altered. At a constant signal, this method classifies as an open-loop application, as no information from the flow field is incorporated. While the open loop control approach proves to be an effective control approach, the drawback lies in the fact that the output doesn't change and adapt with changing flow conditions. It is also hard to account for disturbances and model uncertainty.

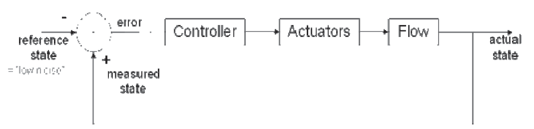


Figure 2. Closed Loop Control

An ideal control strategy would adapt with the changing dynamics of the flow field, thus rendering passive techniques unattractive [6]. Closed loop control optimizes control authority, while minimizing the energy needed to generate the control signal. The control signal is not constant, instead it changes based on the changing flow conditions. The current sets of experiments of interest build upon previous efforts, initially aimed at developing an understanding of the turbulent flow structure of the jet, by attempting to develop a robust, real-time, closed-loop control strategy based on a low-dimensional description of the near-field pressure. Previous studies at Syracuse University using similar closed-loop flow control techniques have demonstrated positive results. In work by Pinier et al. [6], using a low-dimensional description of the fluctuating velocity field over a NACA 4412, a successfully closed-loop control strategy was developed and shown to delay the onset of stall. Work done by Wallace et al. [7] examining flow over a 3-D turret at Mach 0.3 demonstrated, through similar closed-loop feedback using a low-dimensional description of the pressure signature, a resultant more homogenous flow field with a reduction in characteristic time and length scales.

JET NOISE

The jet engine is arguably the single most important and highly researched component of the aircraft in modern day engineering. Among these plethora of research interests exists the mechanism by which the jet generates noise. The noise 'source' in jets has been characterized by the generation, subsequent interaction, and evolution of the coherent turbulence structure, within the shear layer, produced by the mixing between the high-momentum, high-temperature core jet flow and the lower-speed, cold entrained flow, as cited by *Ffowcs Williams & Kempton* [8]. "At the heart of this problem is the challenge of deciphering which events in these high-speed flows are most efficient at radiating highly intense acoustic pressure fluctuations that translate to the far-field as broadband noise" [9]. One can deduce that it is the nonlinear dynamics of the jet which are the source of the noise, but what part of this nonlinear process that generates that noise is not known. It has been affectionately stated by P. Jordan that the "Holy Grail" of jet noise would be to ultimately indentify this source mechanism responsible for the far-field noise.

Today, noise level regulations are becoming increasingly strict within the commercial aviation industry. Within the military, these goals align where stealth technology is concerned. Consequently, many researchers have turned their efforts towards developing techniques aimed at controlling and mitigating these sources of sound [10].

OBJECTIVE

The objective of this study is to use high Reynolds number turbulent compressible jets as a test bed for designing and developing closed loop flow control schemes for mixing manipulation and jet noise mitigation. This jet is the ideal 'platform,' it is canonical in nature and allows careful detailed basic research without sacrificing realism [11]. For this study we closed the loop, utilizing a simple proportional controller for state estimation.

EXPERIMENT

Facility. This study is conducted in Syracuse University's $206m^3$ fully anechoic chamber. The interior chamber specs including sound treatment (wedge tip to wedge tip) are 26ft. x 20ft. x 14ft. The chamber walls are all acoustically treated with 150Hz fiber glass wedges. A more detailed overview of the facility's design and characteristics are described in Tinney *et al* [12]. An overview of the experiment is shown in Figure 3. The axisymmetric nozzle is 50.8mm in exit diameter, and operated at Mach 0.6. The Reynolds number based on this exit diameter is 690,000. The exit conditions of the core flow and the bypass air are matched and held constant at 27° and ambient pressure. Previous experiments in this facility have shown that exit conditions of the nozzle exhibit turbulence intensities on the order of 1% in the potential core, which collapses at 6D in the stream wise direction [13]. The outer shear layer has been shown to spread at an angle 11° with respect to the jet axis, where as the inner shear layer spreads at 5.5°.

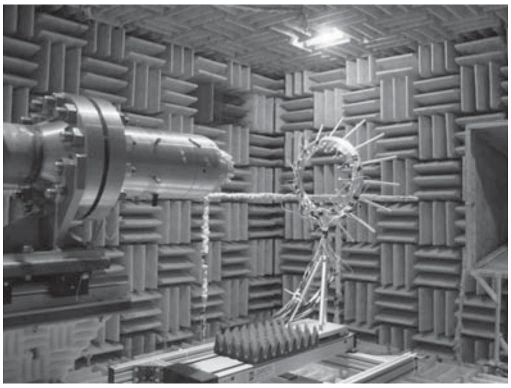


Figure 3. Anechoic Chamber

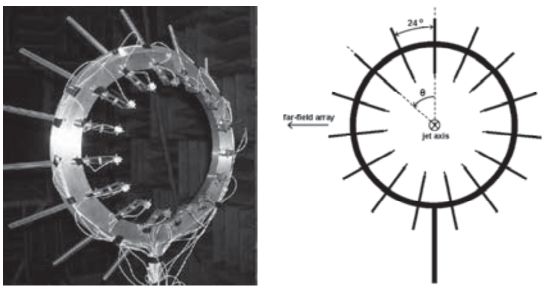


Figure 4. Near-field pressure ring

Instrumentation. Near-field pressure signature is acquired using five *Kulite* model XCE-093-5G transducers at a sampling frequency of 12000 Hz/channel. The transducers are arranged in an azimuthal array; equally spaced 72° apart, at eight diameters (8D) downstream from the jet exit and approximately 1*cm* outside the spreading shear layer; where the pressure field is shown to demonstrate dominant hydrodynamic characteristics and maximum correlation with the acoustic far-field, see Figure 4. The signal from these sensors is transformed to resolve the Fourier azimuthal modes to be used in the feedback scheme.

The far-field noise signature (at x/D=75 diameters) is measured using an arc array of six 1/4-inch G.R.A.S. type 40BE 1/4 inch pre-polarized, free field condenser microphones sampled at 30kHz. These are positioned along a boom at increasing polar angles from φ=15°-90°. The downstream microphone (microphone 6) is positioned at an angle of φ=15° from the jet centerline and arrayed at 15° thereafter, with the sixth (microphone 1) at φ=90° from jet exit. The setup is pictured in Figure 5. The acoustic signature resultant of the control scheme can then be compared to that of the true signal, sample a priori.

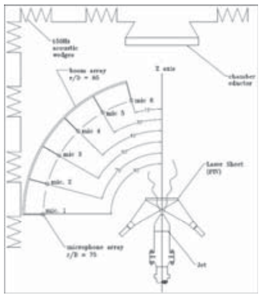


Figure 5. Orientation of far-field microphones

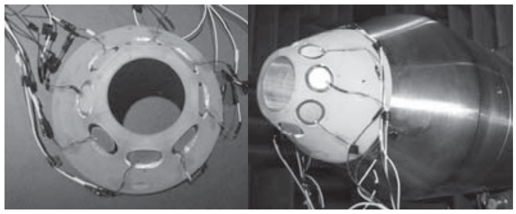


Figure 6. Actuator glove configuration

For control authority, a uniform, circular array of eight synthetic jet actuators producing a zero net-mass-flux was designed and integrated onto the jet nozzle, Figure 6. With this setup we seed the flow with a forcing pattern in the form of modes-0 or -1 of the jet flow. The exit slot for each actuator is located at 0.6mm from the lip of the jet and is inclined towards the jet flow at an angle of 45° for optimal performance. Each synthetic jet actuator consists of a circular piezoelectric diaphragm sealed to a side of a slotted cavity. Covering the piezoelectric diaphragms is an acoustic shield which is intended to minimize the actuator sound from propagating to the far-field. The piezoelectric diaphragm is 1.07 inches in diameter and oscillates at a resonance frequency of 2600Hz. At their optimum frequency of 2600Hz, the synthetic jets are able to produce their highest exit velocity of 55m/s. Thus, the coefficient of momentum per actuator at this velocity is 0.0013 (.13%), based on jet exit velocity and diameter.

The first control case studyed was an open loop control that implemented a constant sine wave with a fixed frequency which was inputted into the synthetic jets. The input frequency was set at the maximum momentum output, which was found using hot wire tests to be at 2600 Hz.

A simple pressure based proportional closed loop feedback controller was implemented to manipulate the shear layer of the jet flow. The controller input is obtained from the near field pressure signal. Since the information from the flow is vast this pressure signal is reduced to a low dimensional system through the use a Fast Fourier Transform in space. Previous work by Hall et al. [18] demonstrated that the modal characteristics of the near-field pressure, sampled within the noise producing region (x/D=6-10), were uniquely correlated with the far-field acoustics. In particular, that the helical azimuthal mode (mode-1) diminished the strength of the correlated signature and the column azimuthal mode (mode-0) correlated the highest with the far-field. Two closed loop cases were explored; the amplitude of mode 0 and mode 1 were inputted into the proportional controller individuality.

The equation below shows the input signal of the proportional controller.

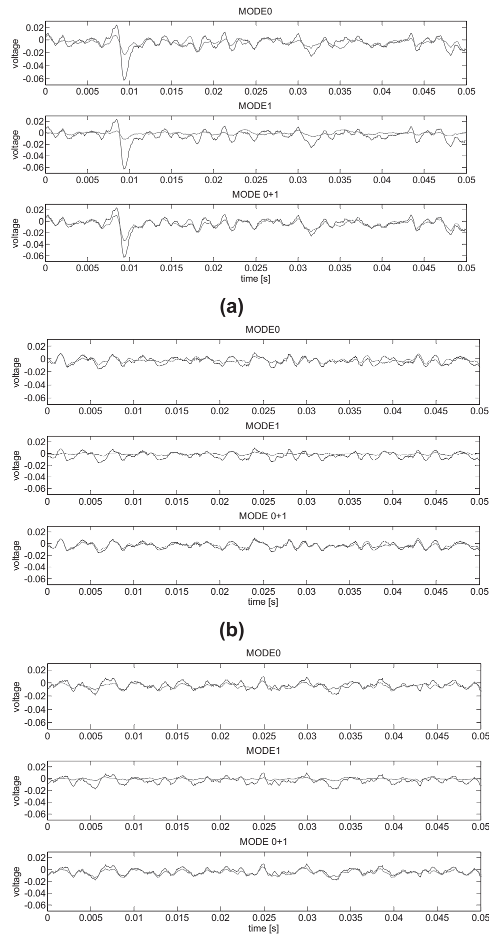
$$u(t) = KA(t)sin(2\pi f_0 t) \qquad (1)$$

In the above equation, u(t) is the input, K is a constant feedback gain, A is the amplitude of FFT mode, and f_0 is the characteristic frequency of the synthetic jet actuators.

RESULTS

Modal Description of Pressure for Controlled Cases. Figure 7a shows a sample time series of the pressure for Kulite 1 at ϴ = 24° (blue) compared to the mode-0 part of the pressure only (top), the mode-1 part of the pressure only (middle), and the sum of both contributions (bottom), for the open loop case. The same is shown in Figures (7b) and (7c) for the closed loop mode-0 case and the closed loop mode-1 case. What we see is in direct accordance with the work of Tinney [14], as well as Iqbal and Thomas [15], for the un-controlled case (baseline) in that, even in an instantaneous sense, both modes are as important to satisfyingly reconstructing the pressure signal. So even though for the controlled cases, we are using flow based amplification to alter the near-field pressure, the jet flow still remains low dimensional. In relation to relative amplitude, it is clear that the open loop case contains higher amplitude peaks, in relation to the closed loop cases. What does this mean? For the open loop case, we are providing a constant mode-0 forcing to the shear layer, whereas, in the closed loop cases, we are only applying actuation when desired.

Feedback Signals and RMS. Figure 8 shows the input signal and the resultant time series of the pressure for *Kulite 1* for each case. In Figure 8a we see the simple sinusoidal forcing at 1900 Hz for the open loop case. Figure 8c shows the feedback signal for the closed loop mode 0 forcing. For these two cases, all the actuators were driven in phase. Figure 8d shows the feedback signal for the closed loop mode 1 forcing case. In this particular case we are feeding back the mode 1 part of the near-field pressure with a mode 1 forcing. By mode 1 forcing, it is meant that the actuators are driven 180° out of phase. There are eight actuators in total. We have the control authority to actuate sets of 4 independently. It is important to note, from an efficiency standpoint, the closed loop cases are more beneficial in that less energy is required for these control schemes. Observation of the pressure time series shows a considerable reduction of the Prms from the open loop case to closed loop case, which corresponds to a reduction in the turbulent kinetic energy. Prms of the open loop case being ≈0.0077, and Prms of the closed loop mode-0 and mode-1 cases being ≈0.0054 and ≈0.0052.



(c)

Figure 7. Time series of the near-field pressure compared to mode 0, mode 1, and the summation of 0 and 1; (a) open loop case, (b) closed loop mode 0 case, and (c) closed loop mode 1 case.

Far-field. The pressure spectra of the far-field microphones are shown in Figure 9. For both controlled and un-controlled cases, the far-field spectrum becomes more broadband as the polar angle increases (φ = 15°- 90°). We know this to be consistent with the known directional nature of the jet acoustic pressure field [16]. Tam & Chen [17] concluded that the weaker and more broadband pressure fluctuations at larger polar angles are a result of the fine scale turbulence in the jet and the larger, more narrowband

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fluctuations at these shallower angles from the centerline corresponds to mixing noise caused by the large-scale vortex structures interacting in the flow. What we can deduce from this is that the actuation is not denaturing the characteristics of the flow. The high amplitude peaks in the spectra are the forcing frequency and its harmonics. At 15° the relative amplitude of the forcing frequency and its harmonics differ between the three controlled cases. It is most prominent in the open loop case. In the closed loop mode-0 case it is prominent, but lower in amplitude. It is almost unnoticeable in the closed loop mode-1 forcing case. At larger polar angles (45^{o} and 90^{o}) the relative magnitude of the forcing frequency and its harmonics increases as the angle increases. Additionally, for each angle the amplitude change between the different controlled cases follows the same trend as the microphone at 15°. For the open loop case, we are exciting azimuthal mode-0. From previous work (Hall *et al.*) [19], it is known that mode-0 is the most efficient propagator to the far-field as noise. It is also known that the higher modes (*helical modes*) do not radiate to the far-field as effectively as the column mode. This may be why the open loop case and the closed loop mode-0 forcing case have higher intensity forcing frequency peaks than the closed loop mode-1 forcing case.

Figure 10a shows the far-field comparison between the three control cases and the baseline case at φ=15 (microphone 6). Overall, we see an increase in noise at lower Strouhal numbers of the jet and a decrease in the noise for higher Strouhal numbers of the jet. The cross-over Strouhal number is at around St= 0.2. Figure 10b depicts the comparison between the open loop controlled case and the closed loop mode-0 case. The overall magnitude of the closed loop mode-0 case is lower than that of the open loop case for the entire frequency space. In Figure 10c we see the comparison of the open loop case and the closed loop mode-1 case. No significant difference in the overall magnitudes can be deduced from this figure. Figure 10d shows the comparison of the two closed loop cases. It appears that the closed loop mode-0 forcing case constitutes the greatest reduction in noise above a Strouhal number of 0.2.

Near-field. The pressure spectra of the near-field sensors are shown in Figure 11. The pressure spectra for the near-field exhibit the same behavior as the far-field spectra. The forcing frequency and its harmonics are most prominent in the open loop forcing case. They are visible in the closed loop mode-0 forcing case, but not as prominent. The amplitude of the forcing frequency is almost unnoticeable in the closed loop mode-1 forcing case. The spectrum for each *Kulite* collapses on top of one another well. There is a slight discrepancy with *Kulite* 4, however the near-field spectra shows azimuthal symmetry in both magnitude and frequency content for all other sensors at frequencies lower than the forcing frequency. At frequencies higher than the forcing frequency, the frequency response is very inconsistent.

CONCLUSIONS

A detailed preliminary investigation of simple proportional closed loop flow control for turbulent compressible Mach 0.6 jet was discussed. The aim was an overall reduction of the far-field noise signature. It was found that for φ = 15° (shallow angle), an overall increase in the sound at lower Strouhal numbers (0.04 – 0.2) of the jet was noticed for all controlled cases. The greatest reduction was noticed for the closed loop mode-0 case. Conversely, and overall decrease in the sound was noticed at higher jet Strouhal numbers (0.2 – 3.7). At φ = 60° and 90°, there was an overall increase in sound pressure level for all controlled cases. We have shown that with minimal observability, minimal controllability, and a very simple proportional closed loop feedback scheme that we were able to achieve a reduction in some jet Strouhal number ranges. Now that we know this closed loop approach is showing promising results we will double back and refine key aspects of the experimental setup and control methodology. Instead of using only 5 *Kulites* in our ring array, we are going to increase the number to fifteen in order to improve our spatial resolution upon performing our FFT. Currently, the actuators we are using for our control authority have a very limited frequency range 100 Hz - 2500 Hz. Although the frequency response of the actuators might be on the same order of magnitude as the dynamics of the flow, Samimy *et al.* [5] has shown that it may be more beneficial to use devices which allow the capability to actuate at frequencies in the exact range of the instability frequencies. From a control standpoint, we plan to incorporate more sophisticated reduced-order models and control systems (*i.e. Kalman filter*). We are also currently using no time lag in our control scheme. Therefore, it is our plan to incorporate a time lag on our feedback signal which corresponds to time lag of the strongest correlation between the near field and far-field data.

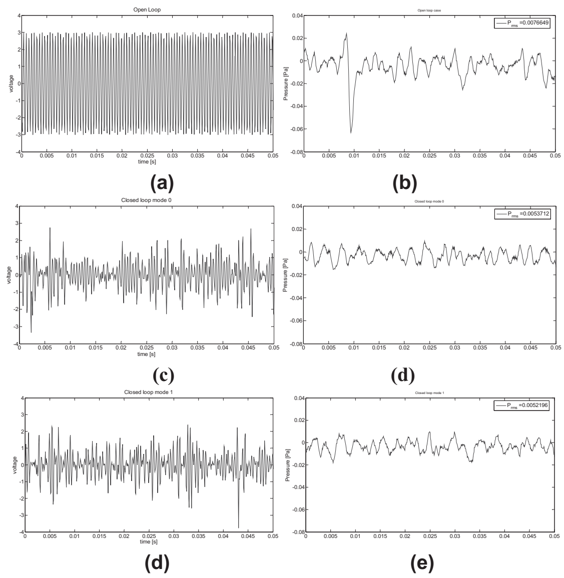

Figure 8. Characteristics of the signal used for control in each case, as well as the resultant time series and RMS of the near-field pressure, (a) and (b) open loop case, (c) and (d) closed loop mode 0 case, and (c) and (d) being the closed loop mode 1 case.

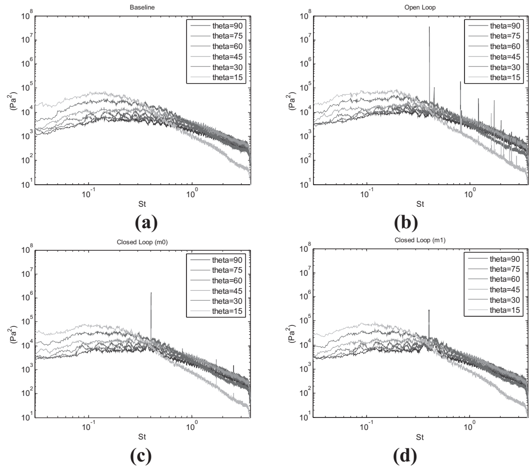

Figure 9. Far-field pressure spectra for (a) baseline case, (b) open loop case, (c) closed loop mode 0 case, (d) closed loop mode 1 case.

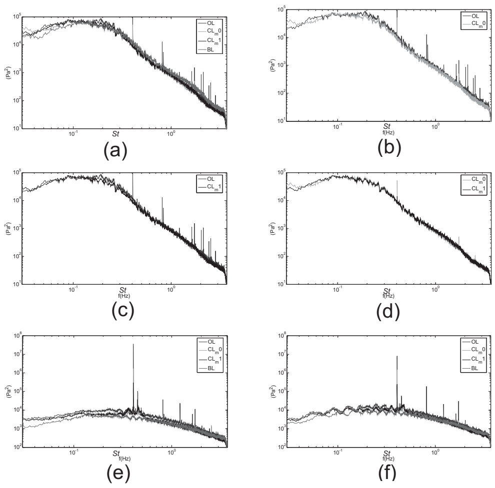

Figure 10. Far-field acoustics for microphone 6 at φ=15° (a - d), far field-acoustics for microphone 3 at φ=60° (e), and far-field acoustics for microphone 1 at φ=90° (f)

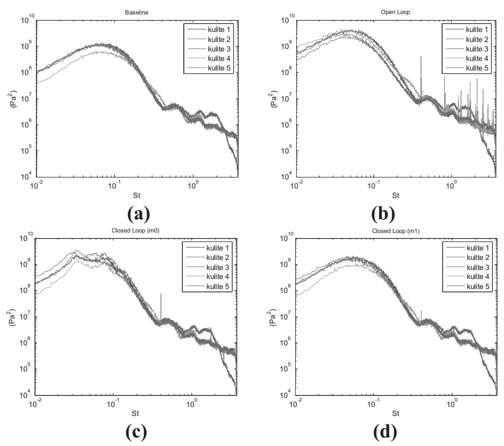

Figure 11. Near-field pressure spectra for (a) baseline case, (b) open loop case, (c) closed loop mode0 case, and (d) closed loop mode 1 case.

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