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AN EXPERIMENTAL INVESTIGATION OF COMBUSTION TURBINE EXHAUST NOISE SOURCES

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INTRODUCTION

As increasing numbers of combustion turbine based power generation facilities are sited closer to residential areas, noise control engineers are continuously challenged to develop more effective and less expensive silencing treatments. In addition to stringent A-weighted requirements, low frequency noise, or infrasound requirements are commonly observed in many sound specifications. While it is widely accepted that infrasound is generated within the combustion turbine's exhaust, the mechanisms that contribute to its generation are not so clearly understood. Typically, the exhaust sound power of a combustion turbine is assumed to be a fixed quantity to be controlled only by the design of the exhaust stack's silencer. Putnam and Parzych[1] have shown the impacts of these silencers, such as the silencer's size, performance impacts and expense, have necessitated a need for a full understanding of the mechanisms contributing to the generation of combustion turbine infrasound. The combustion turbine's exhaust noise spectrum has been shown to be complex, consisting of multiple noise sources. Parzych and Schott[2] have discussed the constituent components of the exhaust spectrum. High frequency exhaust noise, above 1000 Hz to 2000 Hz, is generally dominated by turbine tones. The combustion process generates combustion roar which has been shown in the Aerospace Recommended Practice ARP876[3] to peak in the range of 400 Hz. Noise related to combustion instability, as shown by A. Putnam[4], can be infrasonic. The exhaust flow noise due to aerodynamic interaction with internal support struts or internal engine surfaces, as well as noise resulting from the jet exhausting into the stack's plenum, and flow impingement noise, as shown by Petrie[5], can also contribute to the generation of low frequency noise. Lastly, low frequency noise can be generated by poorly designed flow paths within the stack as well as from poor flow distribution along silencer passages.

In order to design effective treatments for low frequency noise, the sources must be fully understood and ranked. Designing a solution to the wrong noise source is not only ineffective but also expensive. This paper presents the results of an experiment developed to identify the major low frequency noise contributors by showing sound level measurements made within the exhaust stack of nominal 106 MW Westinghouse 501D5 combustion turbines. The results of coherence between combustor dynamic pressure and noise at the stack exit are discussed as well as estimates of the source location made by simulating combustion turbine exhaust noise sources through superposition of a sound source within the exhaust stack and turbine exhaust transition.

BASIS OF EXPERIMENTS

Two Westinghouse 501D5 combustion turbines, nominally rated at 106 MW at ISO conditions in simple cycle configurations, were used as the basis of the experiments. Both combustion turbines exhausted axially into rectangular exhaust stacks. However, one of the units used water injection to control Nitrogen Oxides (NO_x) emissions while the other used dry low NO_x (DLN) control technology. The two experiments were designed to identify the major exhaust noise components with the prime objectives to determine:

1. The contribution of combustion noise relative to flow related noise sources.
2. Whether the main sources of flow related noise are created within the combustion turbine itself or generated within the exhaust stack.

Experiment 1 - Effect of Water Injection On Exhaust Noise. The combustion turbine's combustor baskets were instrumented with dynamic pressure transducers to measure the internal fluctuating pressures. A microphone was also located near the exit plane at the top of the exhaust stack. This enabled coherence to be measured between the combustor dynamic pressure and the sound pressure level measured at the top of the stack. The relative change in sound level at the 16 and 31.5 Hz octave bands could then be correlated with the rate of water injection. The contribution of the combustion noise was separated from the total exhaust noise by use of coherent output power.

Experiment 2 - Aerodynamic Source Location. A combustion turbine equipped with the DLN emission control had acoustic ports located within the exhaust transition and along the side wall of the exhaust stack near the rear wall. A waveguide with an anechoic termination was attached to each of the ports. A microphone was then flush mounted, perpendicular to the inner wall of each waveguide. The sound pressure level within the stack was measured at the transition and at the back of the stack during each of the following conditions:

1. The combustion turbine in its normal base load (106 MW) operating mode.
2. The combustion turbine shut off (cold) and a reference sound source (ILG), located just downstream of the last turbine stage.
3. The combustion turbine shut off (cold) and an ILG noise source located near the back wall of the exhaust stack.

The location of the aerodynamic noise could then be estimated using principles of superposition. For orientation, a graphical representation of the test(s) can be seen in Figure 1.

COMBUSTION NOISE

Stringent air quality regulations have required that emissions control features be integrated into combustion designs. These features, particularly the injection of water or steam into the combustor baskets, have been noted to have the effect of increasing low frequency noise. Previous data, reported by Parzych and Schott[2], showed the sound level at the 31.5 Hz octave band to be strongly influenced by the rate of water injection used to control NO_x emissions. The influence of water injection on other frequency bands is also evident. Figure 2 shows the measured change in sound pressure level at the top of the exhaust stack as a function of water injection rate for the 16 Hz to 250 Hz octave bands. It can be seen that sound pressure levels in the 16 and 31.5 Hz octave bands appear to be strongly related to increases in water injection rate while the higher frequencies appear to be affected less. In general, at frequencies above the 31.5 Hz octave band, it appears that the changes in sound level shown in Figure 2 are due to data scatter (less than ±2 dB) rather than correlation with changes in water injection rate. In any case, the effect is small above 31.5 Hz and will not be considered in the remainder of this paper.

Coherence Between Combustor Dynamic Pressures and Stack Top Sound Pressure. The coherence between the combustor basket dynamic pressures and the stack top measurements can be seen in Figure 3. It is clear that the coherence between the combustors and the stack top improves as the rate of water injection is increased. The coherence at 16 Hz is generally better than at 31.5 Hz. This corresponds well to the data shown in Figure 2 which shows the 16 Hz octave band to have the largest increase in sound level with increasing amounts of water injection.

Estimates of Relative Source Contributions Between Combustion Noise and Aerodynamic Noise Sources. Determining the relative contribution of the combustion and aerodynamic noise sources is a major step in understanding the low frequency noise mechanisms of combustion turbines. To determine the relative contributions of these sources, the coherent output power method was used. Figure 4 shows the estimated relative contribution between the Combustion Related Noise and Total Noise in the 16 Hz octave band as a function of water injection rate. The combustion related noise was then logarithmically subtracted from the total sound pressure to obtain what is labeled as Aerodynamic Noise. It can be seen that the aerodynamic noise is dominant at the lower water injection rates, while combustion noise becomes dominant at higher injection rates. The apparent increase in the aerodynamic noise as a function of water injection rate is likely to be an artifact of the analysis. It is most likely, in reality, that the aerodynamic noise remains relatively constant and the effect shown is a manifestation of the technique used to extract the noise components. The combustion noise is therefore underestimated by 1 to 2 dB at the higher water injection rates. Figure 5 shows a similar trend at 31.5 Hz. The combustion related noise is shown, however, to drop off much more rapidly as the water injection rate is decreased. Although the coherent output power method has been shown by Krajsa[6] and others to underestimate the contribution of combustion noise of aircraft gas turbines by as much as 10 dB in some cases, it appears from these results to be a valid basis upon which to build an understanding of the relative contribution of exhaust noise sources.

AERODYNAMIC NOISE

Aerodynamic noise has been suspected to be a major contributor to low frequency noise generation in combustion turbine applications. However, there are many potential sources of aerodynamic noise. Parzych and Schott[2] have conjectured that sources such as the free jet entering an exhaust stack's plenum can be a significant source of low frequency noise and have shown data exhibiting a strong relationship of velocity to the eighth power. Air impinging on a surface, such as on the back wall of a stack, the interaction of the flow with support struts within the engine, and geometrical irregularities of the silencers and flow paths within the exhaust stack can also contribute to the creation of low frequency noise.

Jet Sources Or Other Sources Of Aerodynamic Noise. Aerodynamic sources typically exhibit a trend of increasing sound level with flow velocity. For dipole sources, a trend of V^6 or $60 \times LOG_{10}(V)$ would be expected, while for quadrupole sources, such as jets, a trend of V^8 or $80 \times LOG_{10}(V)$ would be observed. In either case, it is difficult to discern differences between V^6 or V^8 in actual data due to the rapid rate of change in sound level with relatively small changes in velocity. This is also compounded by the relatively high level of measurement uncertainty associated with low frequency sound, adding to the difficulty of examining these trends. Never-the-less, Figure 6 displays the trend observed from several 501D5 combustion turbines as a function of exhaust gas exit velocity in absolute cubic feet per minute (ACFM). A least squares fit of the data shows a trend of approximately $V^{6.4}$. However, it isn't hard to imagine that the data in actuality may have a steeper slope than the curvefit indicates. In any case, the data clearly shows a strong dependence on some form of aerodynamic noise at low frequencies which can be important when noise related to the combustion process has been controlled.

The remaining question is whether the aerodynamic sources are created in the exhaust stack or within the combustion turbine itself. It is conjectured that if the aerodynamic sound is created in the exhaust stack, the maximum low frequency noise would be found close to the back of the stack where the jet is more fully developed. Also, if the noise is the result of flow impacting with the rear wall, the source would be highest in amplitude near the wall where impact occurs. An experiment was performed to provide insight into the location of the aerodynamically generated noise sources. With a cold stack (engine off), an ILG fan source was first located slightly downstream of the last turbine stage. Sound level measurements were made at the exhaust transition port and at a port located in the side wall of the exhaust stack near the rear wall. The ILG source was moved to the rear wall of the stack and the test was repeated. The sound level measurements were also repeated with the combustion turbine operating. Figure 7 presents the results of the cold test with an ILG source as differences between the sound levels measured at the transition microphone port and the downstream stack port. When the source is located downstream of the last turbine stage, the sound pressure levels at the exhaust transition microphone port were found to be higher than the sound pressure levels measured at the port located near the back wall of the stack. When the ILG source was located near the back wall of the stack, the sound pressure level was found to be higher in the port located near the back wall of the stack . While it is recognized that the exhaust stack would have different modal characteristics when operating at exhaust gas temperatures with flow, the overall trend discussed above was seen at *all* frequencies and is therefore assumed to exhibit a similar *overall* trend when operating hot with the combustion turbine as the noise source. Shown in Figure 8 is the difference in sound pressure level measured at the exhaust transition and near the back wall of the stack with the combustion turbine operating at base load conditions. Since the sound pressure spectrum was higher at the transition microphone port, as was similarly shown when the ILG source was located near the last stage of the turbine, it is assumed that a dominant portion of the low frequency aerodynamic noise is generated within the combustion turbine itself. While this does not conclusively eliminate the exhaust jet and impact noise as significant mechanisms contributing to the generation of low frequency noise in all applications, they appear to be secondary in the application tested.

SUMMARY

Combustion related noise and aerodynamic noise have been conjectured to be substantial generators of combustion turbine low frequency noise. This study has shown that combustion noise can be the dominant source when water injection is used to control the production of NO_x. Aerodynamic noise sources generated within the combustion turbine are likely to be the next major contributors of low frequency noise. Sound generated by the combustion turbine's exhaust jet and flow impacting the rear wall of the exhaust stack are likely to be secondary aerodynamic sources.

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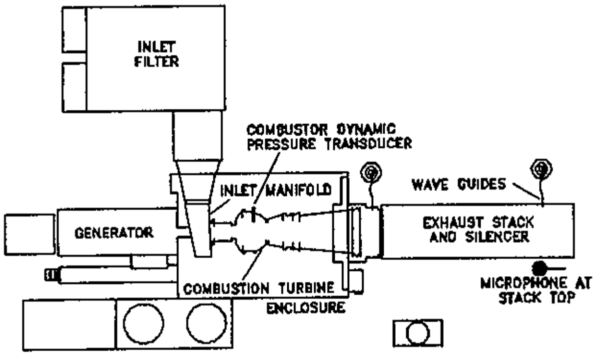


FIGURE 1. SKETCH OF COMBUSTOR COHERENCE AND SUPERPOSITION TESTS

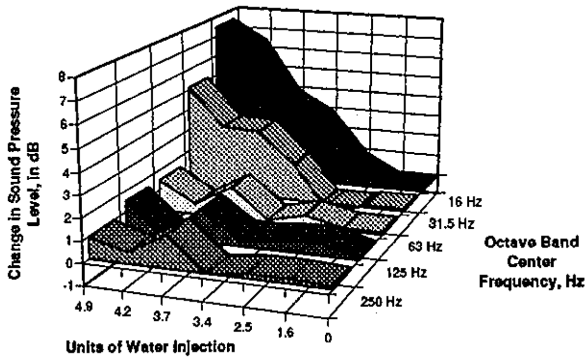


Figure 2. Change in Sound Pressure Level as a Function of Water Injection Rate

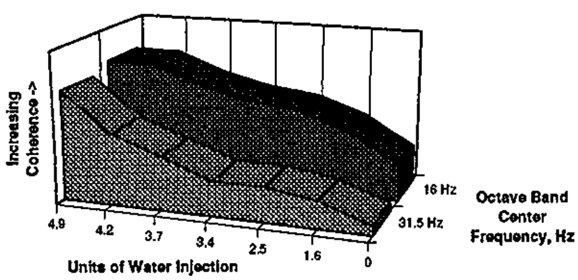


Figure 3. Coherence Between Combustor Dynamic Pressure Measurements and Sound Pressure Level at the Top of the Stack

Figure 4. Relative Sound Level of Combustion and Aerodynamic Sources at 16 Hz Based on Coherent Output Power Estimates

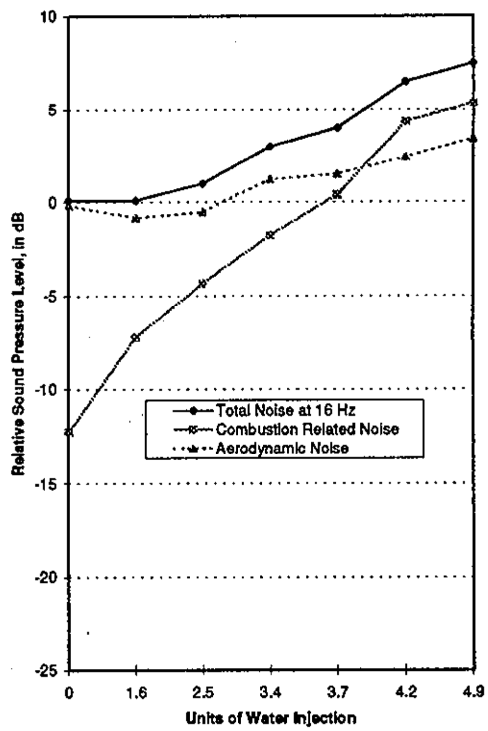


Figure 5. Relative Sound Level Contribution of Combustion and Aerodynamic Sources at 31.5 Hz Based on Coherent Output Power Estimates

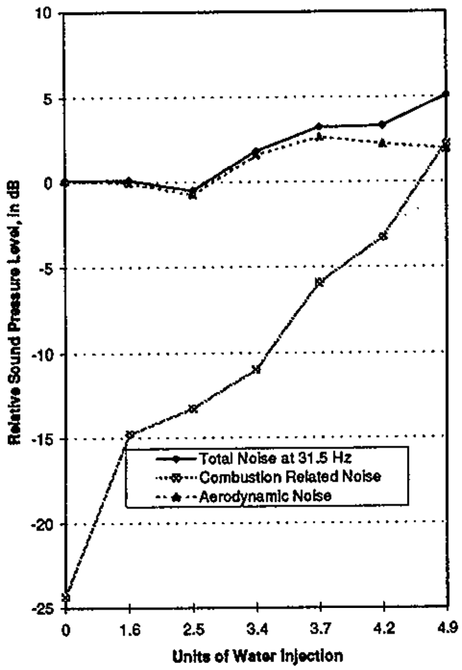


Figure 6. Changes in Sound Pressure in the 31.5 Hz Octave Band with Exhaust Flow

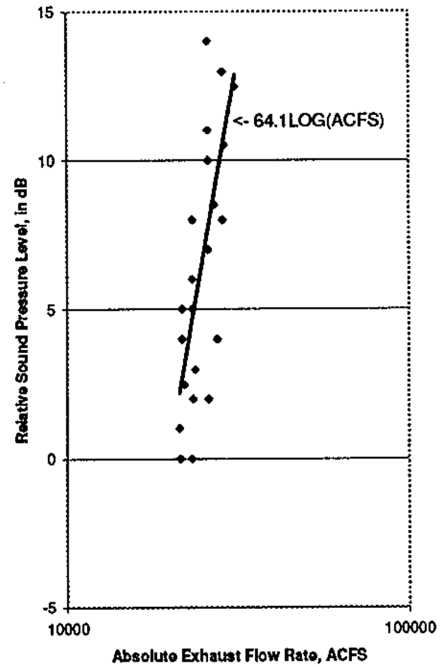


Figure 7. Effect of Source Location on Measured Sound Level (ILG Source with Cold Stack)

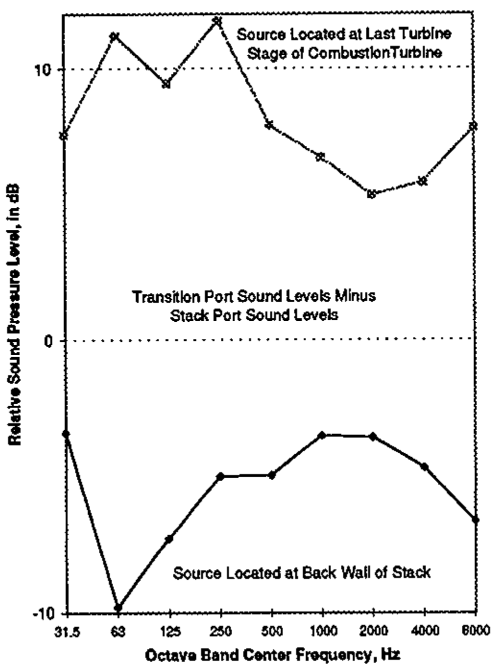
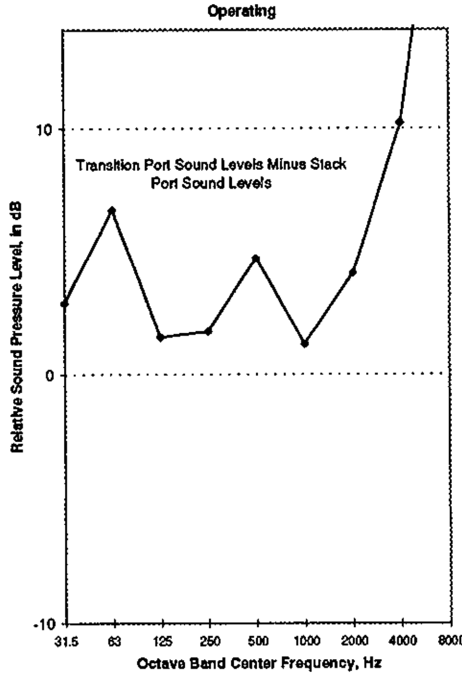


Figure 8. Relative Sound Levels Measured at the Exhaust Transition Probe and at the Probe Located in the Back of the Stack with the Combustion Turbine Operating



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