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ISSUES IN DETERMINING SOUND POWER LEVELS OF GAS TURBINE EXHAUSTS

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1.0 INTRODUCTION

Gas turbine based power generation facilities require customized noise abatement features to achieve various community noise standards or regulations. While many sound sources exist within these facilities, the most complex and costly to silence is typically that related to the gas turbine exhaust. The starting point for all exhaust silencer designs is the accurate definition of the unsilenced gas turbine's exhaust sound power level.

Engineers or acoustical consultants normally specify silencers to be designed using exhaust sound power level data provided by the gas turbine manufacturers. However, manufacturers' data can often be poorly defined, imprecise or erroneous - resulting in over or under design of the exhaust silencing. In cases where the exhaust silencer is suspected of not meeting its guaranteed performance, the silencer designer will typically question the accuracy of the sound power level data supplied in the specification. Currently, there are no existing American or International standards for measuring the in-situ **unsilenced** sound power level generated by the gas turbine air intake or exhaust. While an ASTM working group has been formed to address this issue, it may be several years before any solution is attainable. The lack of an available standard necessitates the need for each consultant or engineer to use his own best judgment to estimate the sound power level of a given gas turbine based on measurements and/or analytical techniques.

This paper describes issues associated with accurately measuring and defining the sound power levels of gas turbine exhausts including problems associated with measuring sound within the confined space of large exhaust gas ducting with hot turbulent flow. Issues associated with duct geometry and defining complex modes are discussed as well as difficulties encountered when using calibrated sound source substitution techniques.

2.0 AVAILABLE TECHNIQUES USED IN DETERMINING THE UNSILENCED IN-SITU GAS TURBINE EXHAUST SOUND POWER LEVEL

There are currently two basic techniques used to determine the in-situ sound power level developed by the gas turbine's exhaust:

1.) A direct method that utilizes sound pressure measurements made within the gas turbine's exhaust ducting using special probes, waveguides or high temperature microphones. Data is typically taken at one or more ports placed within the exhaust ducting. The data is then averaged, if applicable, and corrected for the internal cross sectional area of the ducting to determine the sound power level of the equipment.

2.) An indirect method that utilizes sound pressure measurements made outside of the hot gas flow near the exhaust stack exit plane. The sound data are then corrected for the spherical area of the measurement surface and corrected for the measured or analytically determined sound attenuation characteristics of the given silencing system.

Each of the above techniques has its' own limitations.

While physically measuring sound within hot gas flow using available equipment may appear to be an ambitious enough challenge for most engineers or consultants, the task is further complicated because the data obtained must be representative of the sound power generated by complex turbo-machinery within the confined space of the large ducting. Often, this is accomplished through measurements made in the area immediately downstream of where the gas turbine exhausts into a secondary piece of ducting, such as a diffuser. However, some of the components that make up the gas turbine exhaust spectrum may not yet be developed within this region or the sound field may be impacted by the differences in duct geometries that exist at each facility or application. In any case, determining the "true" emitted sound is difficult at best since in some instances, the source of sound may not have existed if the connected ducting had been a different geometry[1].

Limitations also exist in the use of silencer system attenuation characterization for determining unsilenced sound power levels of gas turbine exhausts. Sound measurements made within the ducting or external to the ducting at ambient temperatures using loudspeakers as sound sources do not account for the effects of flow and temperature on silencer performance. These "cold" measurements must then be corrected by analytical prediction methods, requiring a large leap of faith that the theory matches the as-built silencer performance. While many analytical silencer prediction methods are generally quite adequate at predicting the acoustical performance of a silencer with uniform materials and in the presence of hot uniform gas flow at the design stage, the methods typically lack the ability to definitively estimate as-built silencers with non-uniform materials or within actual non-uniform flow environments. The inability to account for these real life affects limits the use and reliability of the silencer characterization technique for determining the sound power level of an in-situ gas turbine exhaust.

3.0 APPLICATION OF IN-DUCT SOUND PRESSURE MEASUREMENTS

Two major issues are associated with determining the sound power level from sound pressure level measurements made within exhaust ducting:

A. The environment for performing such testing is incompatible with standard acoustical instrumentation.
B. It is nearly impossible to accurately define, with limited measurements, the complex acoustical modes generated by the gas turbine's combustion process, turbine tones, buzz saw noise, jet noise and flow interaction noise. All of these unique sound sources are lumped together and referred to simply as, "the gas turbine's exhaust sound spectrum."

A. Instrumentation and Flow Issues Associated With In-Duct Measurements

With gas temperatures often exceeding 1000° F and localized flow velocities exceeding 300 fps, engineers and consultants have developed various techniques to measure the sound within the hot gas environment. These techniques use either specially designed, usually proprietary, microphones capable of withstanding the high temperatures that can exist within the gas path or a more common technique that utilizes a waveguide system to isolate a standard microphone from the direct hot gas path. Waveguide systems are typically designed to measure sound impinging on the inner skin of the ducting, as depicted in Figures 1 and 2. Variations of the waveguide system also exist that allow a tube fitted with a nosecone to physically enter the ducting and probe within its' cross section. In general, all waveguide systems utilize tubes that penetrate the ducting. The sound internal to the ducting is then measured by a microphone perpendicularly mounted to the tubing. The tubes are attached to anechoic terminations (a finite length of tube or hose) to prevent end reflections from distorting the data. All tubing and anechoic terminations are generally uniform in cross section to assure standing waves do not exist within the waveguide system.

In either the hot microphone or waveguide case, each system must cope with fluctuating pressure effects resulting from the highly turbulent exhaust flow. The turbulent exhaust flow can tend to overwhelm the acoustic signal, much like high winds do when measuring environmental sound. Since pressure transducers (microphones) measure both the acoustic waves and the varying dynamic pressure signal associated with the turbulence, the data collected is not necessarily representative of the sound that will be observed in the far field. To minimize the effects of turbulence, internal surface mounted waveguides are often placed within dead flow or low flow areas of the ducting. Surface mounted microphones or waveguide tubes also have the benefit of existing within the duct's boundary layer to help minimize the fluctuating turbulent pressures. Probe tubes that protrude into the flow are fitted with nosecones.

An example of a measured sound spectrum, using the duct wall mounted waveguide system within an exhaust diffuser, is compared to manufacturer's sound power level data in Figure 3. While manufacturers' data are not always reliable, the data from which this comparison is based is generally considered by silencer designers to be among the most reliable and usually leads to silencers that perform as expected in the field. It appears that reasonable agreement can be obtained between manufacturer's data and measurements made using the waveguide system. However, it is not known how representative the data is of the "true sound power level" developed by the gas turbine exhaust other than that the data usually leads to successful silencer designs. In this case, it is assumed that the turbulent dynamic pressure has a minimum effect on the measured "sound" presumably generated by the gas turbine exhaust.

Another way of rejecting fluctuating pressure caused by turbulent flow is through signal enhancement. Currently, the use of Coherent Output Power (COP) is in favor among some consultants[2] as a means of eliminating the fluctuating gas pressure from the "true" gas turbine sound. However, the coherence function is not magic. It assumes that the source of excitation at the reference transducer is free of extraneous noise and nearly fully representative of the sound source we are trying to identify at some other point downstream of the reference signal. To accomplish this, we usually place the reference microphone directly aft of the gas turbine exhaust within the exhaust diffuser. The assumption that the reference microphone is the best obtainable representation of the sound source, however, leaves one questioning the benefit associated with using the coherence function for this application. For COP to work properly, the position of the reference microphone must also be optimized for a given sound source. If located in a non-optimum position, the coherence method can provide misleading information. For instance; if the location of the reference microphone is too close to the gas turbine exit, a given sound source, such as a partial free jet, may not yet be fully developed. In this case, the coherence function would not recognize the sound source as being related to sound generated within the gas turbine proper. Another instance would be if the reference microphone probe were positioned within a node of a standing wave or more complex modal pattern. In this case, the reference microphone would likely be contaminated by extraneous pressure fluctuations caused by localized noise or turbulent flow and mask the existence of an actual sound source that may appear at higher amplitudes well downstream of the reference microphone. In any case, the coherence at a downstream position will always be less than unity and will likely lead to significantly lower estimates of the gas turbine's exhaust sound power. This observation agrees with Krajsa[3] and others who have shown COP to significantly underestimate the contribution of sound sources generated within aircraft gas turbines in previous studies. Shown in Figure 4 is an example of coherence seen between two planes within an exhaust diffuser of a large commercial gas turbine unit. It can be seen that the coherence is often poor which can indicate the in-duct sound measurements are not true sound at all but mostly fluctuating gas pressures caused by turbulence. The coherent output power, in this case, could lead the analyst into believing the "true" sound power level is as much as 20 dB quieter than a direct measurement would indicate. However, it is the author's experience that designing noise abatement using sound power levels 20 dB quieter than that supplied by the manufacturers or that directly measured within the exhaust diffuser would result in seriously undersized silencers.

Coherent Output Power does have some limited diagnostic potential. For example, COP can be useful if we are trying to determine the affect of some noise attenuation device (possibly a silencer) that can't be measured above the dynamic pressure fluctuation within the gas flow. However, COP not only discriminates between the reference signal and dynamic pressure fluctuations but also between the reference signal and the self generated noise component of the silencer itself. The silencer's self generated noise is therefore removed by the coherence signal processing which inevitably could lead to the inaccurate conclusion that the silencer is performing well when in fact the silencer may be limited in its' attenuation capability by generating a substantial self noise component.

B. Defining The "True" Sound Emitted By The Exhaust Sound Sources

While it is likely that engineers and acoustical consultants can resolve and agree on how to take measurements within a hot, highly turbulent gas flow environment, we face a more complex issue on how to measure, within the confined space of a large duct, the sound generated by complex turbo-machinery that is also representative of its' true exhaust sound power level.

Because major sound sources may not be fully developed within the gas turbine diffuser, and with the possibility of strong standing waves existing within the exhaust ducting, it is highly unlikely that we can accurately define the low frequency sound power level of the gas turbine unless the geometry of the ducting attached downstream of the engine proper is identical from installation to installation. Since this clearly will never be the case, the best that can be obtained is a "quasi" sound power level that exists at the gas turbine diffuser or some location downstream of the gas turbine.

High frequency tonal sound is also a significant portion of the gas turbine sound power spectrum. The high frequency sound is generally controlled by rotor-stator interaction noise creating spinning modes[4]. To resolve these complex circumferential lobes or modal patterns within the exhaust duct would require a tremendous number of measurements to be made within the ducting and a corresponding large number of closely spaced holes for the duct probes. Large numbers of holes penetrating the ducting is something most plant owners/engineers do not embrace - often limiting the number of allowable penetrations to less than 10. With a limited number of in-duct probe measurements, it is possible to entirely "miss" the high frequency tonal noise sources. "Missing tones" have been noted on occasion by consultants performing these types of in-duct sound measurements.

To demonstrate the difficulty of accurately defining turbo-machinery sound within a duct, the author has measured sound within the ducting of a gas turbine air inlet system. While turbulent gas found within an exhaust diffuser has typical axial velocities near 300 fps, the air flow within the inlet ducting is often less than 40 fps and nearly laminar. Thus, measuring within the air inlet system can help to minimize the unknown associated with the highly turbulent hot exhaust flow. Figure 5 presents measurement locations at two vertical measurement planes within the inlet duct. The planes were approximately 8 feet apart. At each of the planes, three ports were oriented vertically and spaced 4 to 5 inches apart. A total of six ports were measured. All ports were on the "noisy" side of the inlet silencer. Figure 6 provides the results of the sound pressure level measurements. It can be seen that a great variation of sound pressure levels exist within the ducting. At the 31.5 Hz and 63 Hz octave bands, variations as large as 17 dB were observed between the two measurement planes. In the 2000 Hz octave band, the blade passage tone was observed to range in amplitude by 10 dB. The low frequency variations may be caused by standing waves or dynamic pressure fluctuations while high frequency variations are likely caused by inadequate definition of the modal patterns.

Multi-port sound pressure levels are often averaged to obtain the "true" sound pressure level. This assumes that the peak sound has been found and that the distribution of sound is adequately defined. However, with the limited number of ports allowed by the plant owner, it is impossible to determine if the maximum sound has been located.

4.0 IMPLIED SOUND POWER FROM EXTERNAL SOUND PRESSURE MEASUREMENTS

Indirect methods have also been used for determining the sound power level of the engine exhaust.

One such method involves substituting a calibrated noise source of known sound power within the exhaust ducting immediately exiting the gas turbine. The sound is then measured at the exit plane of the exhaust stack with the calibrated sound source in place and the gas turbine engine off. The sound is later measured with the gas turbine operating at its' normal operating conditions. The difference in sound pressure level observed between the operating gas turbine as the source and the calibrated sound source and is then added to the known sound power level of the calibrated sound source to determine the sound power level of the gas turbine. While this method may seem to be straight forward, the temperature and flow differences alter the performance of the attenuation provided by the system. The temperature and flow effects are significantly more complicated than simple shifts in frequencies to account for wavelength differences[5]. For instance, the impedance of silencer materials is grossly altered by temperature and flow conditions. Thus, the performance of the system is not fully characterized until an analytical "adjustment" is made to the measurements. The magnitude of the adjustments casts a doubt on the credibility of the measurements as justification for determining the true sound power level of the sound source.

Another method used in determining sound power level of the engine exhaust is based on measuring sound at the stack top with no silencer in place. While this may be reasonable at a test stand, it is not typically an option in an actual operating facility application. Also, as previously discussed the exhaust ducting alone introduces its' own uncertainty to the data. In addition, some assumptions and accompanying corrections are needed to eliminate stack top vertical directivity effects, elbow attenuation effects, end reflection effects, etc. Without these corrections, these inherent attenuation effects can be doubly accounted for when designing silencing.

5.0 CONCLUSIONS

With all the issues associated with in-duct measurements as well as the complexity of the gas turbine exhaust sound sources, developing a common ground for determining the exhaust sound power level of an in-situ gas turbine will require a great deal of work among the acoustical community. An ASTM Task Group, E33.08I, has been formed to review and determine if measuring in-duct sound power of a gas turbine is feasible and if a consensus can be reached on how or even what to standardize on. While undoubtedly the task group will resolve some of the issues, the million dollar question will always be, "can gas turbine sound power level *ever* be measured to meet a reasonable degree of accuracy?"

6.0 REFERENCES

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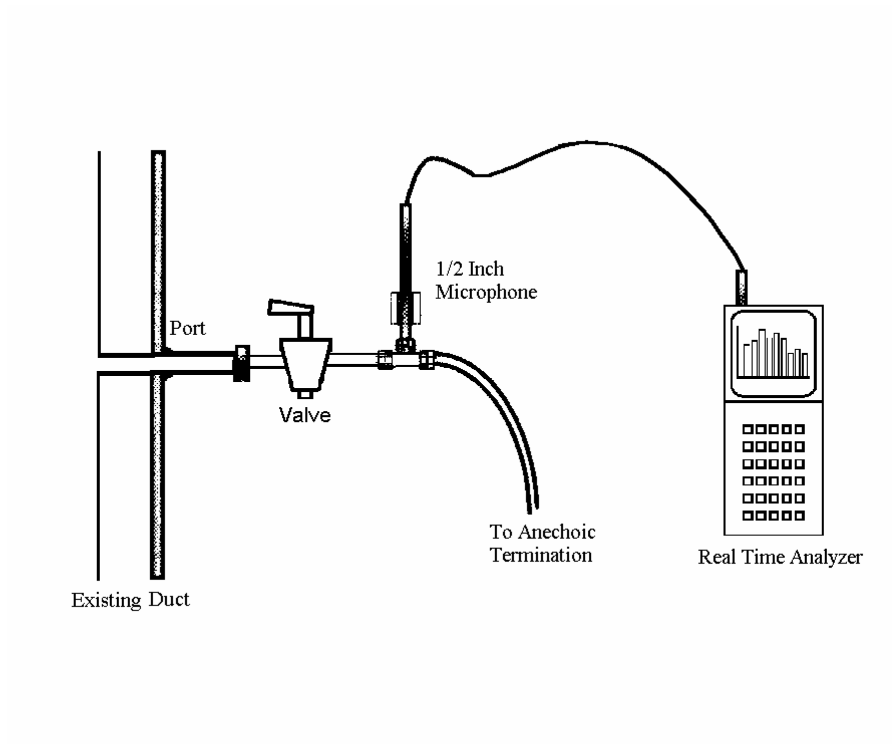

Figure 1. Concept of Typical Waveguide Measurement System

Figure 2. Example of Actual Waveguide Measurement System Installed on Gas Turbine Exhaust Duct

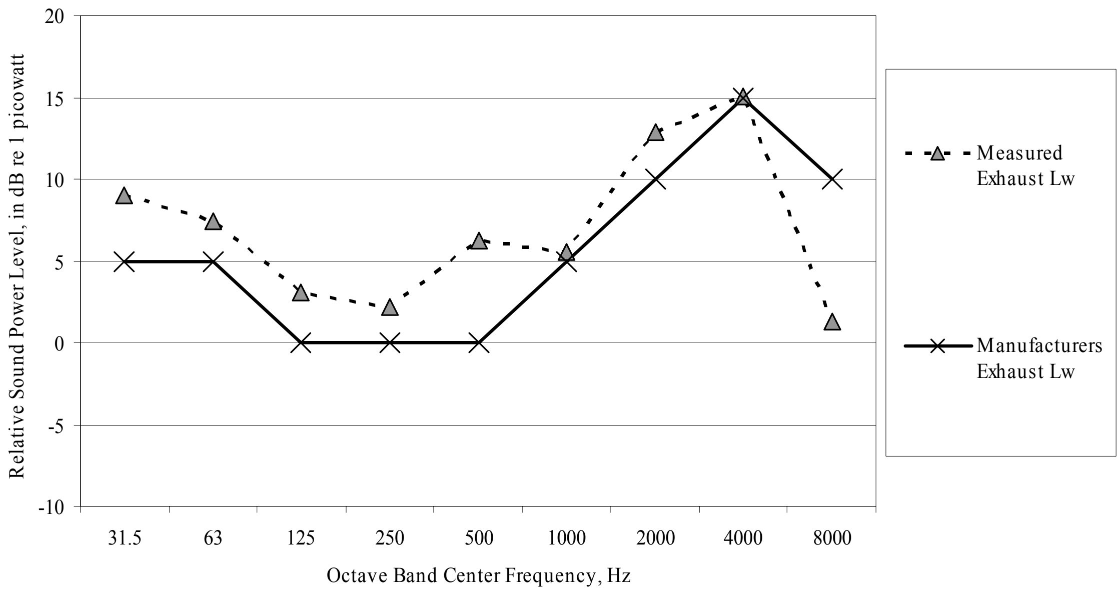

Figure 3. Comparison of Manufacturers Sound Power Data and Measurements Based on Direct In-duct Sound Pressure Levels

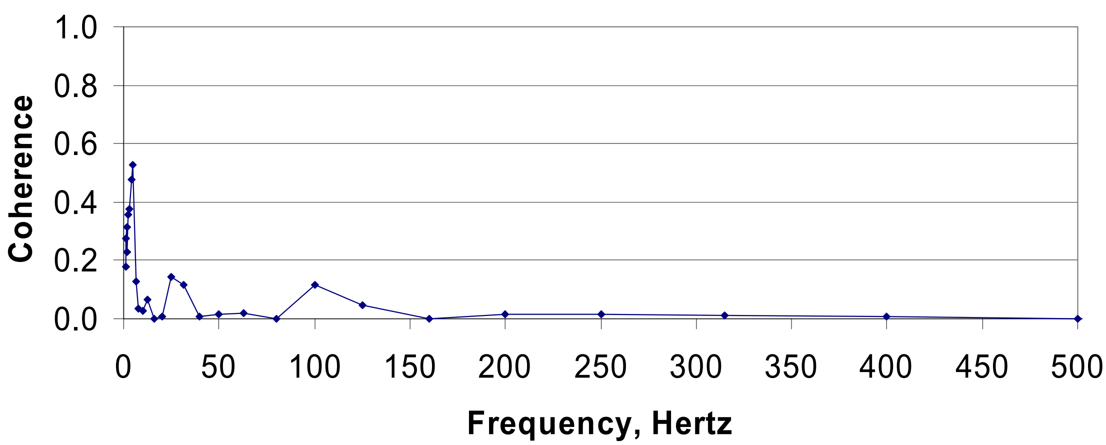

Figure 4. Example of Coherence Measured In Two Planes of a Gas Turbine Diffuser

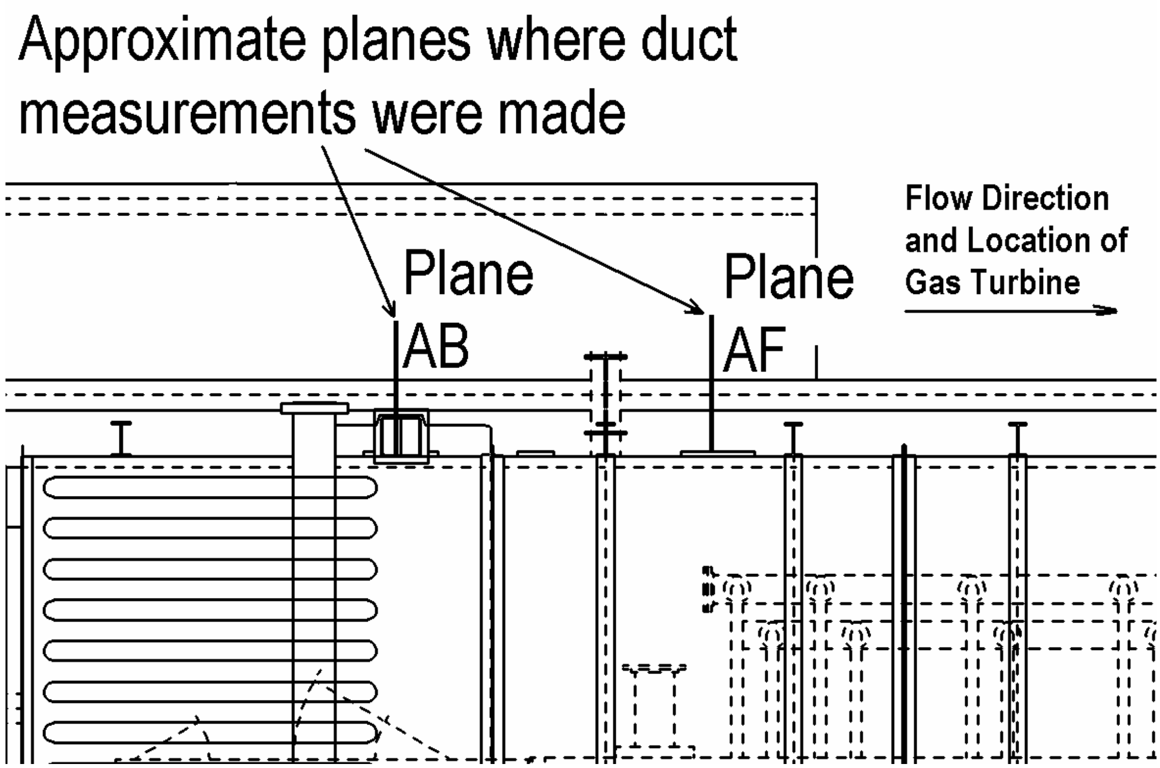

Figure 5. In-duct Sound Measurement Planes of a Gas Turbine Inlet System

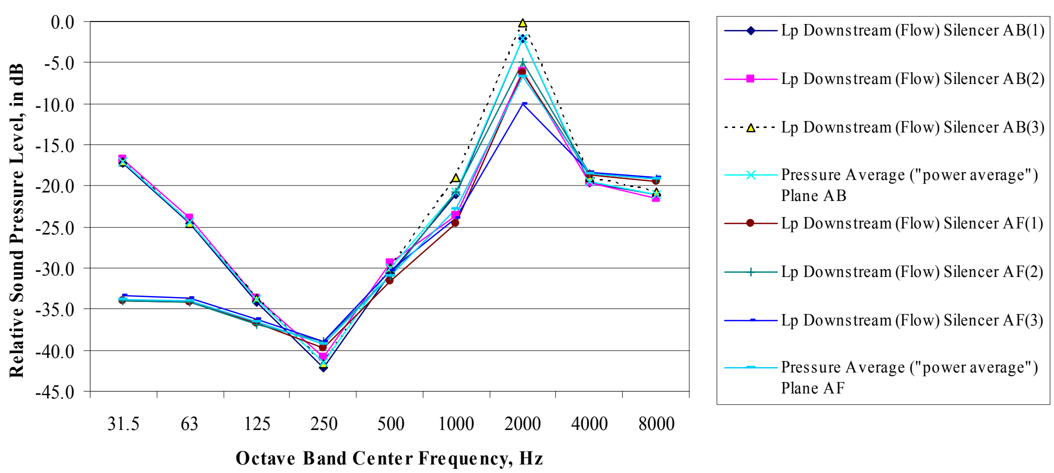

Figure 6. Variations Observed Within Six Different Ports at Two Different Vertical Planes On The Unattenuated Side Of A Gas Turbine Inlet System

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