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UNDERSTANDING THE NOISE GENERATION MECHANISMS OF INDUSTRIAL COMBUSTION TURBINES AND DESIGNING EFFECTIVE NOISE CONTROL TREATMENTS

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INTRODUCTION

Recent trends in siting power generation facilities closer to populated areas has required industry to design low noise features into many of the power plant designs. While industrial combustion turbines continue to play an important role in meeting the electrical needs of the world, they can be a significant noise source if silencing features are not properly designed. State and local noise regulations and ordinances require the plant to be within compliance at the property line and within the community. Also, plant owners and operators are typically requiring low noise levels near the equipment to minimize worker exposure. The noise spectrum produced by the unattenuated stationary combustion turbine is similar to that of aircraft jet engines: broad in nature, containing high frequency components resulting from the blade passage frequencies of the compressor and turbine, as well as low frequency noise components resulting from the combustion process and exhaust flow. Attenuating the broad frequency range of these machines with conventional silencing can be costly in projects where community noise and reduced employee sound exposure are a priority. Understanding the noise generation mechanisms of the industrial combustion turbine is essential when developing new designs and also for developing cost effective noise control treatments. Although the industrial combustion turbine is similar in many ways to aircraft engines, subtle differences exist between the noise generation mechanisms.

This paper discusses the approach of applying source noise reduction technology to new industrial combustion turbine designs as a means of reducing the cost of "add-on" noise control for inlet and exhaust systems. The concepts developed for use in quiet aircraft engine design are explored as well as necessary modifications required when applied to the industrial machines. The discussion includes the similarities and differences between aircraft engines and industrial combustion turbines while also addressing potential silencing strategies when developing a new system design.

THE COMBUSTION TURBINE POWER PLANT

An industrial combustion turbine based power plant may effectively be described as a large jet engine coupled to an electrical generator without some of the obvious aero components like the thrust producing turbofan and nacelle. A cut-away view of a nominal 165 Megawatt (MW) Westinghouse 501F industrial combustion turbine is shown in Figure 1. While typically surrounded by an enclosure, the industrial engine draws air through an intake filter and parallel baffle silencer into the intake manifold and then exhausts into either an exhaust stack fitted with an absorptive parallel baffle silencer or a heat recovery steam generator (HRSG). The remainder of the plant equipment consists of heat exchangers and other auxiliary equipment needed to support it's operation. The general arrangement for a simple cycle plant is shown in Figure 2.

The combustion turbine inlet and exhaust silencing is typically designed based upon tests, analysis and assumptions made for the sound power level spectrum emitted by the engine. The sound power levels are used to design silencer baffle configurations and wall construction requirements. The noise levels emitted by the combustion turbine have historically been assumed to be independent of the design of the inlet or exhaust system silencing and have been assumed to show no dependence on the amount or type of inflow distortion or generation of new dipole sources from flow impact or self noise.

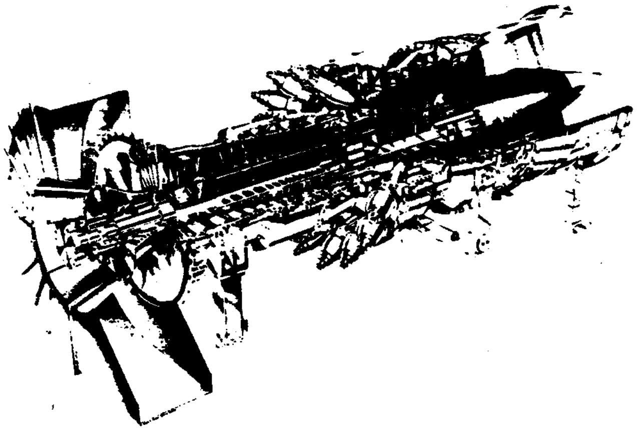

Figure 1. Westinghouse 501F Longitudinal

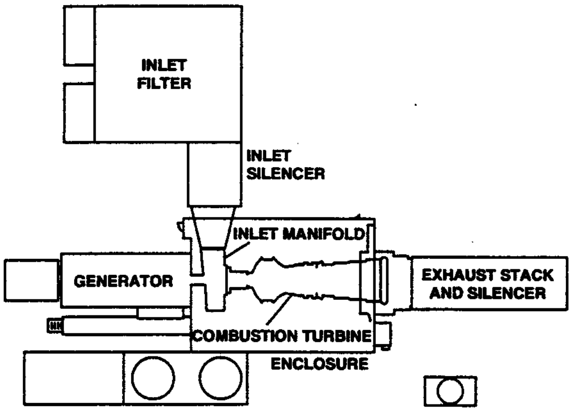

Figure 2. Simple Cycle Combustion Turbine Power Plant

COMBUSTION TURBINE NOISE COMPONENTS

The noise generation sources of the combustion turbine are similar to those of the aircraft jet engine. The inlet is dominated by high frequency compressor tones and harmonics, while the exhaust is dominated by combustion noise, jet noise and turbine tonal components. The typical distribution of sources can be seen in Figure 3.

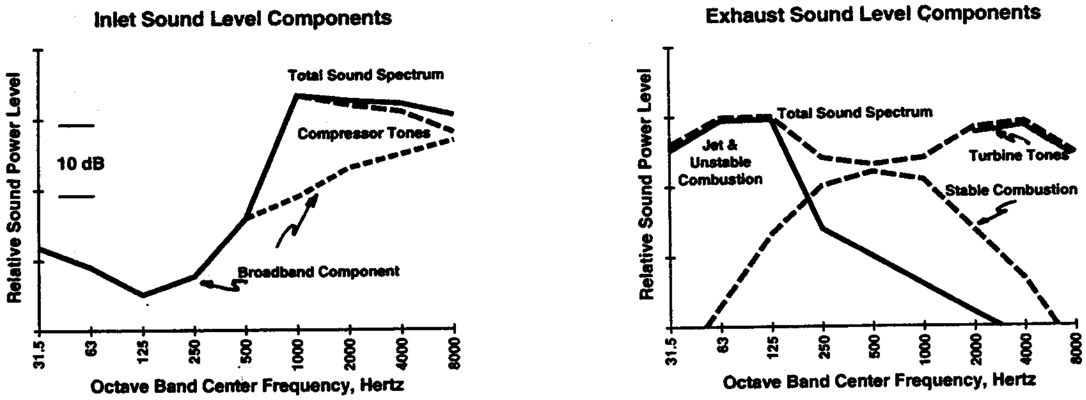

Figure 3. Combustion Turbine Source Distribution.

INLET NOISE COMPONENTS

The inlet noise is largely dominated by blade passage frequency harmonics of the first stage compressor. While sound can propagate from components further downstream, such as higher compressor stages, the combustors and turbine, the levels tend to be significantly attenuated by the time they reach the inlet plenum and are generally not observed as dominant noise sources.

The first stage of the industrial combustion turbine compressor is usually preceded by a set of variable pitch inlet guide vanes (IGVs). At startup and low power conditions, the IGVs are partially closed to preswirl the flow in the direction of rotation to improve efficiency and maintain exhaust temperature. The preswirl also reduces the tip relative mach number of the first stage compressor with a corresponding reduction in noise over the normally open IGV position. However, at the majority of operating conditions, the open IGVs result in higher tip relative mach numbers with increased noise levels. Figure 4 shows the change in sound pressure level inside the inlet duct with and without preswirling. It can be clearly seen that the first stage compressor is the major contributor to the inlet noise.

To develop strategies of controlling compressor noise, one must first understand the mechanisms involved in the noise generation process. Noise generation from rotors can be broken down into two categories; self noise and interaction noise. It has been shown by Tyler and Sofrin[1] that the duct prohibits the tonal component of self noise from radiating along the duct when the rotor in operating at subsonic tipspeeds. Also, a broadband noise component is observed, but is usually small in comparison to the rotor's tonal sources.

Self Noise. The rotor's self noise has both tonal and broadband components. The tonal components are expressed as either a monopole or dipole source. The monopole source, otherwise known as thickness noise, results from the rotating blades periodically displacing a volume of air equal to that of the blade volume. The dipole source is caused by steady lift and drag forces that rotate with the blade, producing periodic pressure oscillations in the air due to the rotation. The tonal self noise components, however, cannot radiate in a duct as noise until the rotor blade tip mach number becomes sonic, as shown by Tyler and Sofrin[1]. The tonal self noise components may prove to be substantial noise sources in transonic compressor designs.

The broadband components of rotor noise can be related to several components. Viewed simplisticly, the broadband noise can be explained as randomly occurring fluctuations due to boundary layer vortex shedding or from randomly acting blade loading caused by turbulence entering the rotor.

Interaction Noise. A major source of compressor tonal noise in industrial combustion turbines is due to the interaction of the wakes from the IGVs with the first stage compressor rotor. As shown in Figure 4, the link between the position of the IGVs and the in-duct rotor noise is strong. The cause of the interaction noise is depicted in Figure 5. A trail of wakes is formed behind the IGVs causing a velocity deficit in the flow field. As the rotor passes through the wakes, the velocity deficit causes the rotor to observe a fluctuating air angle along with a corresponding fluctuation in the lift force. The fluctuating pressures on the blade surfaces form a moving pressure pattern in the duct which can radiate as noise. A similar phenomenon occurs when the rotor wake sweeps past and impinges on the downstream swirl recovery vanes. However, because the relative velocity of the stationary vanes is typically much lower than that of the rotor, the sound radiation efficiency is usually small in comparison. The theory developed by Tyler and Sofrin[1] has mathematically shown that the circumferential velocity component of the swept interaction pattern must be supersonic for modes to propagate along a duct. Modes with subsonic speeds do not propagate to the far field and are said to be "cut-off".

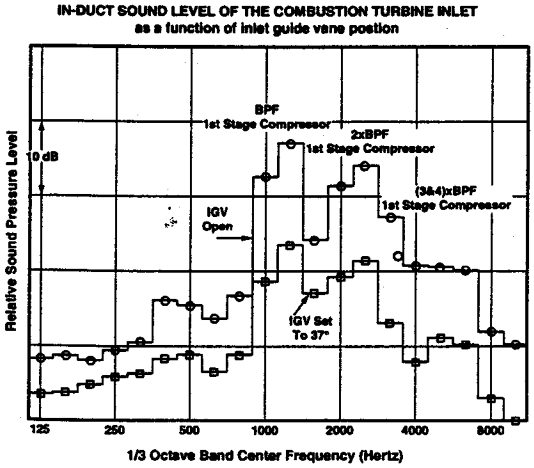

Figure 4. Effect of Inlet Guide Vane Position

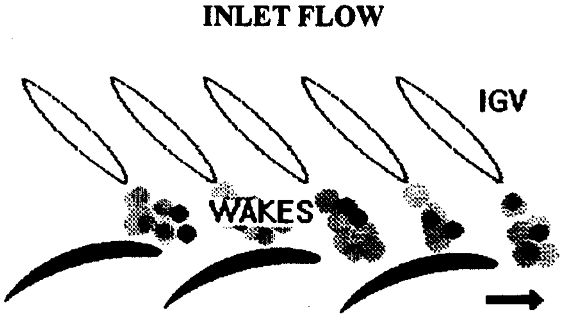

Figure 5. Vane/Blade Wake Interaction

The speed of the spinning mode can be found to be: $\frac{mB}{|mB+kV|}M_t$

where:

m is the sound harmonic of the blade passage frequency and can take on values from 1 to ∞,
B is the number of rotor blades,
k is the harmonic of the fluctuating air load; from -∞, ... -1,0, 1, ... ∞,
V is the number of vanes,
M_t is the tip mach number of the rotor.

When the above expression is greater than 1, the mode is said to be cut-on; when it is less than 1, the mode is cut-off.

It should be noted that the rotor's tipspeed can be subsonic while the moving pressure pattern can be supersonic. The selection of appropriate combinations of blades and vanes can result in reduced blade-vane interaction noise by forcing the blade passage frequency to be cut-off. In instances where the interaction noise cannot be cut-off, the noise can be reduced by increasing the spacing between the blades and vanes to reduce the strength of the wake interaction.

Differences Between Aircraft and Industrial Compressor Noise Suppression. Radiation patterns resulting from the various blade/vane wake interactions can also be controlled by blade and vane numbers. In typical aircraft applications, it is desirable to select the numbers of vanes and blades to provide cut-off of at least the rotor's blade passage frequency. In addition to creating the cut-off phenomena, significant effort is made to avoid modes that propagate away from any acoustically absorptive treatment on the nacelle walls. These modes are specifically avoided by selecting particular combinations of vane and blade numbers.

In industrial applications, the cut-off technique can also be used effectively in the design. However, since all propagating modes eventually reach the inlet manifold, the beamed pattern of the propagating mode is not as critical as for aircraft applications. An acoustically absorptive liner in the inlet plenum and duct can be used as an effective treatment.

EXHAUST NOISE COMPONENTS

The exhaust noise is more complex than the inlet in that more sources produce dominant levels of noise, as shown previously in Figure 3. When operated within a stable regime, the combustors can generate a broadband spectrum typical of combustion roar. Low frequency tonal components can be produced when the combustion process becomes unstable. High frequency turbine tones and harmonics are generated in a manner similar to that of the compressor, while the exhaust gas entering an exhaust stack or HRSG can develop a low frequency rumble characteristic of jet noise.

Combustion Noise. The combustion process of the industrial combustion turbine adds an additional dimension and measure of complexity when compared to that of the aircraft engine. Stringent air quality regulations and standards require that emissions control features be integrated into the combustion designs. One technique used for control of nitrogen oxides, or NOx, is to inject water or steam into the combustor baskets. This lowers the temperature within the combustor baskets and reduces the formation of NOx. The addition of water or steam can push combustion dynamics to the edge of instability, resulting in a greater likelihood of combustion driven oscillations. Putnam[2] has shown that combustion driven oscillations in industrial burners can be observed at low frequencies as relatively narrow bands of high level noise. Similar observations have been seen in the industrial combustion turbines. However, operating in a region of high dynamic pressure at low frequencies can be detrimental to the life of the combustors as well as other components in the combustion turbine and plant design. Typically, combustion turbine manufacturers set limits on combustor dynamics to prolong the life of the components. More recent combustor designs are based upon a dry, lean, premixed design. These dry low NOx combustors limit flame temperature and NOx formation by premixing the air and fuel prior to ignition. The importance of combustion dynamics in the new dry low NOx combustors is of equal importance as the diffusion flame designs with diluent injection. At stable conditions, when no significant combustor driven oscillations exist, one would expect the broadband sound level of the combustors to approximate a typical combustion roar noise spectrum as that shown by Putnam[2] and various other sources such as S.A.E. ARP 876D[3] with a peak in level at about 400 Hz. However, sound level measurements taken on combustion turbines have shown that the amount of water or steam injection can produce significant variations in the low frequency sound content seen in the exhaust. Figure 6 shows the sound pressure level variation as a function of water injection rate for a combustion turbine. As can be seen, sound levels in the 31.5 Hz frequency range increase with increased injection rates. Although the low frequency sound shows a clear dependence on the rate of injection, it is not clear if the sound is developed in the combustor, or if it is a catalyst for generating noise via some other mechanism.

Turbine Noise. The turbine noise sources are similar to those discussed previously in the compressor section. However, where the compressor noise has a dominant blade passage frequency and harmonics only from the first stage compressor, the turbine can have a significant amount of sound emitted from most, if not all, of the stages.

The turbine noise can be controlled by using favorable blade/vane ratios and increasing the spacing between rotating and stationary components. Although this can increase the overall length of the turbine, the value of reducing the turbine tones can be realized when designing the absorptive parallel baffle exhaust silencer. By reducing the high frequency turbine tones, the silencer can be tailored to attenuate the lower frequency combustion and jet related noise components. The optimized silencer may result in a smaller number of parallel baffles to be fabricated with a corresponding reduction in cost or pressure drop.

Jet Related Noise. The exhaust gas exiting an industrial combustion turbine into an exhaust stack or HRSG behaves quite differently than the classical free-jet. First, the classical dependence on jet velocity, known as Lighthill's[4] V^8 law, has been shown by Bushell[5] to break down when the jet core is not laminar and exhaust speeds are close to that of an industrial combustion turbine, or in the range of 100 meters per second or less. Second, the exhaust gases usually impinge on a stack or HRSG surface before the jet is fully developed, thus modifying its characteristic behavior. Work published by Bell[6] and Petrie[7] have shown that the result of a jet impinging on a solid boundary is to increase the acoustic power above that of a free jet by producing a new dipole source. The combination of the low gas velocity and surface impingement makes estimating the contribution of the jet to the total exhaust sound power level difficult. The data discussed previously suggests that the combustors play the dominant role in the low frequency component of the industrial combustion turbine's exhaust sound power level. However, the measured trend in sound pressure level with increasing exhaust gas flow shown in Figure 7 can lead one to believe that the jet is the controlling source. The trend shown was observed when the combustion turbine power output was increased from part load to full load. It is clear that the trend closely resembles the classic V^8 dependence of the free jet. The strong dependence on water injection rate shown previously clouds the issue in that both trends appear to play a primary function at the same frequency. One possible explanation may be an interdependence of the combustion stability and the stability of the jet.

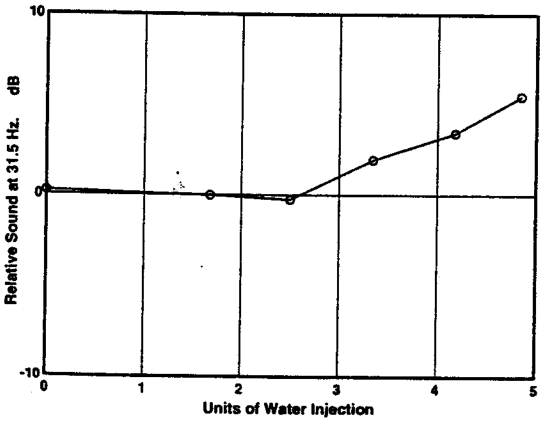

Figure 6. ***Effect of Water Injection on on Low Frequency Noise***

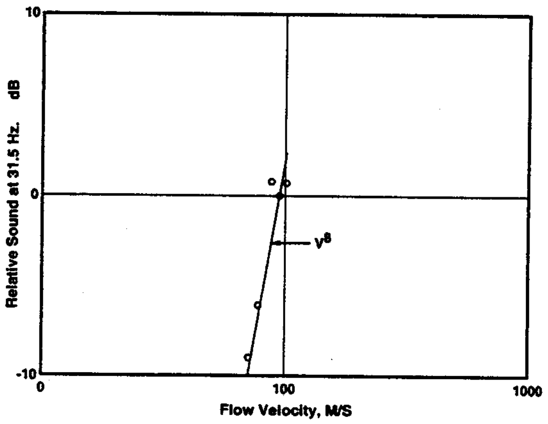

Figure 7. ***Effect of Exhaust Flow on Low Frequency Noise***

Controlling Jet Source Noise. The jet sound level can be controlled most easily by slowing down the exit velocity of the jet or shifting the peak frequency of the jet by selecting various exhaust diffuser schemes. One such scheme may be the use of a slotted diffuser which creates many smaller jets with a corresponding shift to a higher peak frequency. The higher frequencies can then be easily attenuated with relatively short silencers tuned to attenuate the higher frequency noise. Also, Petrie[7] and others have shown that impingement noise can be reduced by sloping the surface at the location of impingement such that the flow direction is not normal to the surface. In any event, the type of noise control implemented in a design can affect the apparent sound power level generated by the combustion turbine. This may help explain why some silencer designs have better apparent performance than can be accounted for theoretically, while others have poorer performance.

PERFORMANCE RELATED ISSUES

While the aerodynamically generated noise of the industrial combustion turbine can be controlled to some extent at the source, absorptive parallel baffle silencers will still be necessary to meet the low noise level requirements of today and tomorrow. Most of us would strongly object to living within a couple hundred meters of even the quietest of today's aircraft. While achieving cut-off of some blade passage frequency tones and harmonics in the compressor and turbine can be desirable, it should not be done at the expense of the combustion turbine's efficiency. Even with the quietest of aircraft designs, cut-off is typically not achieved at more than the blade passage frequency and first harmonic and generally only at the outer most rotor stages. The ultra efficient compressor and turbine designs of the future rely on thin blade technology to minimize profile drag. Therefore, adding or subtracting blades or vanes to cut-off blade passage harmonics may not be practical, especially when a silencer is still necessary to attenuate the lower frequency noise components. However, in design situations when blade or vane numbers can be slightly changed without performance impacts, it can be used as a means of minimizing the cost of add-on silencing.

SUMMARY

The noise of the industrial combustion turbine can be controlled at several stages and should be viewed as a system rather than as a noise source with an inlet and exhaust silencer. At the combustion turbine design phase, the noise can be controlled through the selection of appropriate blade/vane combinations and spacings of the compressor and turbine stages, a stable combustion design, and well distributed low velocity exhaust flow. The inlet and exhaust silencers and the selection of appropriate locations within the system for the placement of the acoustic treatment can then be integrated into the combustion turbine design phase to optimize performance while minimizing cost. In some cases, the type of silencing selected can actually modify the apparent sound power level emitted by the inlet and exhaust of the combustion turbine. A poorly designed exhaust stack can actually generate additional noise due to flow impacting the walls or by causing poor flow distribution within the silencer passages.

While the apparent sound power level of the combustion turbine can be treated in a conventional way by increasing silencer length and using high surface weight wall designs, it may be more effective to find the cause of the noise and reevaluate the design of the system.

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