# Impact of Emission Regulations on Future Gas Turbine Engine Combustors

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**Two hundred and twenty-four low emission gas turbine research combustors were tested under the following future low emission gas turbine combustor categories: (1) Modified Conventional Combustors and 2) Advanced Low Emission Combustors. Modified Conventional Combustors, featuring airblast fuel injectors and primary zone fuel/air ratio control, have marginal feasibility for meeting existing EPA 1979/81 aircraft emission regulations.[1] Further stringency in the emission regulations would require Advanced Low Emission Combustors, which have demonstrated a 90% emission reduction. However, they incorporate features that at current technology levels will require compromises in gas turbine engine size, cost, durability, reliability, and cycle efficiency.**

## I. Introduction

AIRCRAFT gas turbine engine combustors have always had a wide variety of design and performance requirements. These include: minimum size and weight, long durability, low cost, minimum pressure loss, good exit temperature pattern, high combustion efficiency at all main operating conditions, wide stability limits, and wide ignition limits (including altitude).

Many of these performance requirements are in mutual conflict. This is the main reason for the lengthy combustor development effort often required to reach an over-all engine satisfactory performance compromise. A further requirement, exhaust emission control, has now been added to the above list of traditional combustor requirements by Environmental Protection Agency (EPA) regulations.[1] Initial control will begin with engines manufactured January 1, 1979, followed by more stringent regulations in 1981. This paper discusses 1) the impact of these regulations on future aircraft gas turbine combustor design and 2) the impact on combustor design were the EPA to impose requirements more stringent than the 1979/81 regulations.

## II. Conventional Combustor Emissions

The key pollutants relative to the EPA regulations are CO and $NO_x$. Smoke and UHC have less independent significance. Smoke is formed in local primary combustion zone regions of high fuel concentration and high temperature. In such regions the fuel is cracked to carbon and smoke. Smoke control is based on removing either of the two smoke prerequisites. Techniques that avoid regions of very high fuel concentration are generally used. These include airblast atomization and other methods of rapid air addition to the fuel spray. Although the technology to achieve smoke reduction is available, smoke reduction on existing engines is not a trivial task. Extensive effort is usually expended to achieve the required smoke reduction while maintaining adequate performance in other areas.

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Unburned hydrocarbons (UHC) are formed as early intermediates in hydrocarbon fuel oxidation and are readily reacted to CO. In the absence of excessive quenching, the UHC emissions therefore parallel CO emissions, but at a very low level. This has been substantiated at DDA with both Modified Conventional and Advanced Low Emission Combustors. Figure 1 is a plot of UHC and CO emissions for various engines from idle to maximum power.[2] CO and UHC emissions are proportional to the UHC about a factor of 10 below the CO emissions. Figure 1 indicates that, in general, when the CO limit is reached, the UHC is also achieved. UHC is strongly influenced by the extent of reaction quenching in the wall cooling film layer or other chilled primary zone regions so that wide UHC variations exist for different designs. In the best conventional designs, the UHC limit is reached *before* the CO limit. (This is also the case for the Advanced Low Emission Designs, to be discussed in Sec. V.) Also, UHC emission has little independent significance in a properly designed low CO combustor. For these reasons, control of CO and $NO_x$ will be emphasized in the subsequent discussion.

Reaction kinetics analysis shows that CO is necessarily formed in large amounts as an intermediate in hydrocarbon oxidation. It must then be consumed to give low exhaust emission values. The CO oxidation process ($CO + OH \rightarrow CO_2 + H$) is relatively slow and is favored by reactive conditions of high temperature, long residence time, and high pressure.

$NO_x$, on the other hand, is formed through a competing side reaction of oxygen and nitrogen present in the combustor primary zone. Its *formation* is favored by the reactive conditions which favor CO *consumption* (high temperature, long residence time, and pressure). Temperature has the strongest effect because it relates to $NO_x$ formation exponentially.

The consequence of the CO and $NO_x$ formation processes is that conditions or combustor design changes which improve $NO_x$ emissions generally worsen CO performance and vice versa. In view of this tradeoff characteristic, a comparison of individual CO or $NO_x$ performance can be misleading from an over-all emission performance standpoint. An assessment of emission technology is therefore best made from an $NO_x$ vs CO emissions plot, Fig. 2.

Figure 2 includes data from a wide variety of combustion systems and operating conditions: 1) DDA, P&W, and GE designs; 2) Low pressure ratio, low burner outlet temperature (T63 nonregenerative) to high pressure ratio, high burner outlet temperature designs (GMA100-Gas Generator); 3) Regenerative designs (T63 regenerative);

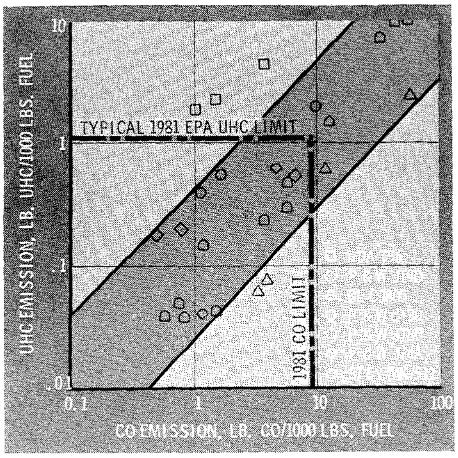


**Fig. 1 CO and UHC relationship for conventional gas turbine engine combustors.**

**Table 1 EPA LTO duty cycle—class T-2 aircraft**

| Mode | % Power | Duration |
|---|---|---|
| Taxi/idle (out) | as specified | 19.0 min |
| Takeoff | 100 | 0.7 min |
| Climb | 85 | 2.2 min |
| Approach | 30 | 4.0 min |
| Taxi/idle (in) | as specified | 7.0 min |
| | | 32.9 min |

4) Idle power to maximum power conditions; and 5) Single can (T63), to can annular (T56) to full annular designs (GMA100, GMA300).

Over this wide range of conditions and configurations, the emission results define a relatively narrow band. This band defines the conventional combustor emissions technology level. For any given combustion system, idle operation has relatively high CO and low $NO_x$. Low power points therefore fall toward the indicated "Idle" region. High points have high $NO_x$ and low CO and therefore plot toward the indicated "Max" region. Many changes (discussed in Sec. IV) can be made to the conventional combustor to change emissions. The CO and $NO_x$ will tradeoff in such a way as to remain on the Fig. 2 conventional emissions band. A true technology gain would shift the whole CO-$NO_x$ curve toward the origin, i.e., achieve simultaneous reductions in CO and $NO_x$ emissions.

## III. EPA Emission Regulations

The EPA recently passed regulations for the control of aircraft engine emissions over a standardized landing and takeoff (LTO) cycle to 3000 ft altitude. Table 1 summarizes the LTO cycle for aircraft gas turbine engine class T-2. This is the 8000 lb thrust or greater turbofan engine class. Similar EPA regulations have been formulated for turboprop and other engine classes.

The cycle is strongly weighted with low power settings. Initial emission regulations over the Table 1 duty cycle occurs in 1979, followed by more stringent control in 1981. The Class T-2 emission limits are summarized in Table 2.

Since the regulations (except smoke) are expressed in terms of lb pollutant/1000 lb thrust-hr/cycle, the engine cycle efficiency has a direct influence on the EI performance required from the combustor. The general relationship is

$$EI_{REQ}\left(\frac{\text{lb pollutant}}{\text{1000 lb fuel}}\right) = \text{EPA Index}\left(\frac{\text{lb pollutant}}{\text{1000 lb thrust-hr}}\right) \times \frac{1}{\text{SFC}}$$

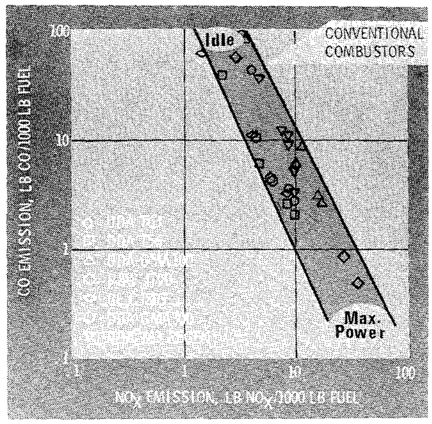


**Fig. 2 CO-$NO_x$ emission performance of conventional gas turbine engine combustors.**

**Table 2 EPA aircraft emission regulations—Class T2**

| Pollutant | Emission limits[1] 1979 | 1981 |
|---|---|---|
| $NO_x$[a] | 3.0 | 3.0 |
| CO[a] | 4.3 | 3.0 |
| UHC[a] | 0.8 | 0.4 |
| Smoke[b] | 31.0 at 10,000 $lb_f$<br>22.0 at 30,000 $lb_f$ | same |

[a] Lb pollutant/1000 lb thrust-hr/cycle.
[b] EPA Smoke number—function of engine thrust.

where

$$\text{SFC} = \text{lb fuel/lb thrust hr.}$$

Therefore efficient engines (low SFC) have relatively high combustor EI allowance, as shown in Fig. 3. For this paper, an advanced technology turbofan with an LTO cycle weighted SFC of 0.35 was chosen.

Integration over the Table 1 duty cycle gives the average CO and $NO_x$ EI limits to meet the EPA regulations. Figure 4 compares these limits with conventional combustor technology. Since the conventional emission technology band traverses the CO/$NO_x$ limits for 0.35 to 0.50 SFC engines, Modified Conventional Combustors have the basic potential of meeting the EPA limits. If the emission limits are further reduced or if the SFC is higher than approximately 0.50, then the conventional combustor would not have the potential for meeting regulations. Advanced Low Emission Combustor designs then become mandatory. These technology levels are discussed in Secs. IV and V.

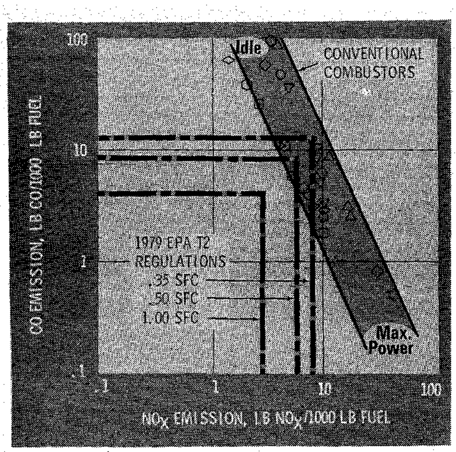


**Fig. 3 Effect of engine SFC on combustor emission requirements.**

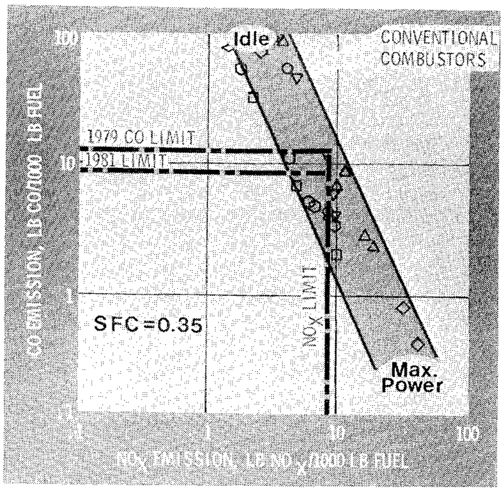


**Fig. 4 Conventional emissions vs EPA regulations for T-2 class aircraft gas turbine engines.**

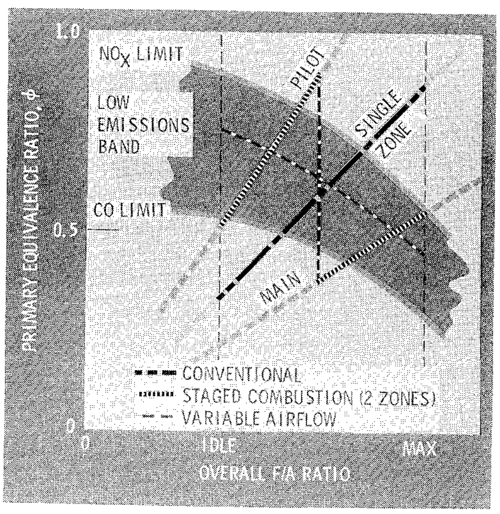


**Fig. 5 Primary equivalence control through variable airflow and fuel staging.**

## IV. Modified Conventional Combustor

At DDA, many changes to the conventional combustor have been experimentally evaluated for low emission potential in the course of a program to reduce total mass emissions 50% from a single can combustor without increasing a single constituent emittant.[3] These changes include: airblast and air assist fuel injection; rich primary zone; lean primary zone; reduced wall cooling flow; increased combustion volume; early quench and delayed quench; reverse flow primary zone; and optimum primary (hole size, number, location, swirl).

Airblast atomization reduced smoke by leaning locally rich hot fuel pockets which encourage fuel cracking to carbon and smoke. Reduced cooling airflow reduced UHC and CO emissions originating in the cold airlayer next to the combustor walls. Other changes, such as leaning the primary zone were effective in reducing $NO_x$ emissions.

In general, changes that decreased $NO_x$, increased the CO emissions (and vice versa) so that mainly a CO-$NO_x$ tradeoff was made. The resulting emissions still fell on the conventional emissions band. The demonstrated tradeoff capability is extremely important in reducing emissions over a specified duty cycle. *Combinations* of several low emissions features provided a maximum *simultaneous* emission reduction up to 50%.

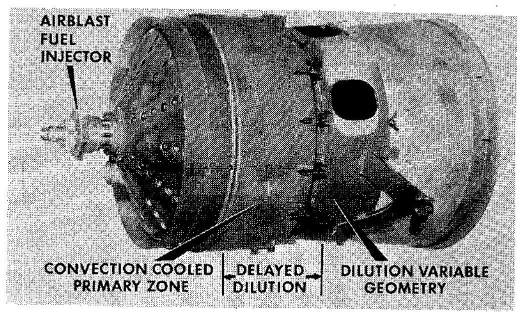


**Fig. 6 T63 Modified Conventional Combustor.**

Extensive changes to the conventional combustor were also evaluated. These include: water injection, variable primary airflow,[3] and staged combustion. The most effective water injection method gave significant $NO_x$ reduction with only moderate CO increase. However, due to logistics, safety, and durability, water injection is not considered an acceptable method for aircraft applications.

Variable primary airflow, staged combustion, and idle compressor bleed are features that improve control of the primary zone equivalence ratio and emissions over the power-operating range. This improved control may also be necessary for stability and ignition performance. These qualities may be compromised by combustion designs optimized for low emissions. The control of primary combustion zone equivalence ratio with variable primary airflow or fuel staging is illustrated in Fig. 5, showing the primary zone equivalence ratio band required for low emissions over the engine f/A operating range. On such a plot, a conventional primary zone operates on a straight line passing through the origin, so that the optimum emissions band is exceeded at some conditions. A staged combustor can operate on two or more zones (lines through the origin) so that a much better "match" is obtained over the operating range. Variable airflow provides the greatest control that allows an ideal match to emission requirements over the operating range. Either approach is a major modification to the conventional combustor. Test results of both of these at DDA showed, as expected, that no basic emission reduction is achieved with variable airflow or fuel staging. These features are useful, however, in maintaining emissions performance over a range of conditions, in "tuning" emissions to specific emission requirements, and in providing greater flexibility for obtaining stability and ignition performance.

Current EPA regulations can probably be met with such modifications to the conventional combustor. A T63 Modified Conventional Combustor is shown in Fig. 6. This combustor met EPA regulations for its class. Its design incorporated four low emission features: 1) convectively cooled primary zone, 2) airblast fuel injection, 3) delayed dilution zone, and 4) variable geometry (two position).

The first three features provided a basic emission reduction of 50% through reduced wall quench, improved fuel/air mixing, and increased residence time. The variable geometry provided the proper primary zone equivalence ratio over the operating range. Two-position variable geometry control was adequate for this particular design. This simplified the mechanical and control systems. Another two-position variable airflow control is compressor idle bleed. This raises combustor primary fuel/air ratio for improved CO-UHC emission. Mechanically this is a very attractive scheme. Detail studies show that the Modified Conventional Combustor might in some cases meet the EPA regulations without any variable airflow capability at all. Table 1 modal emissions might lie outside the Fig. 4 EPA "boxes," as the emissions varied over the power range, but the integrated emissions value could

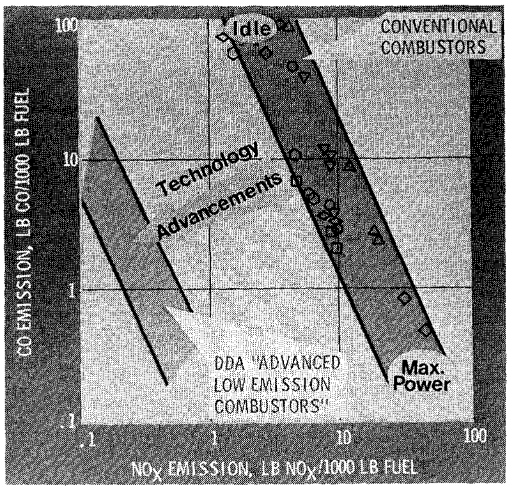


**Fig. 7 Advanced Low Emission Combustor emission results.**

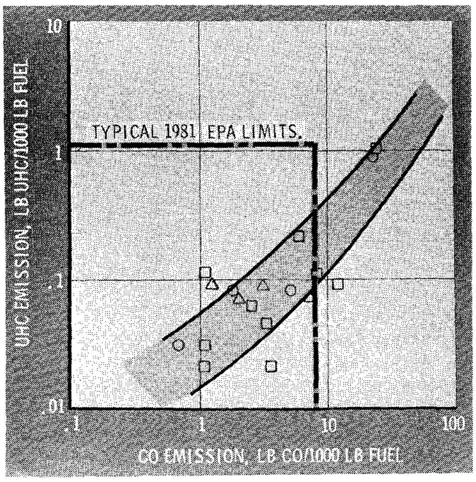


**Fig. 8 UHC-CO emission performance of "Advanced Low Emission Combustors."**

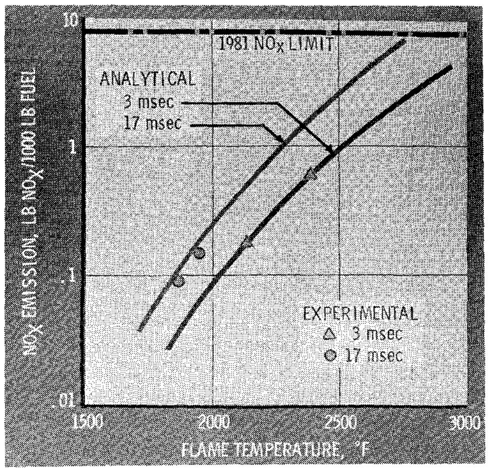


**Fig. 9 Effect of temperature and residence time on $NO_x$ formation (experimental and analytical).**

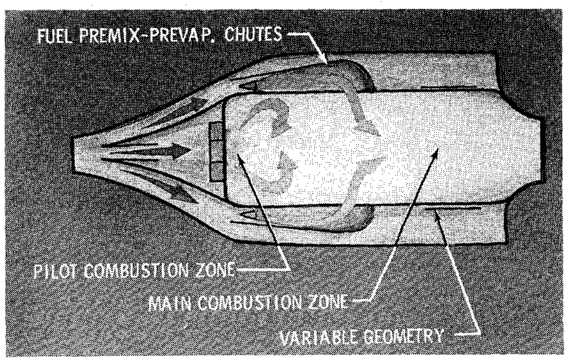


**Fig. 10 Advanced Low Emission Annular Combustor.**

meet EPA regulations. This prospect becomes even more likely for a combustor having a basic 50% emission reduction through a combination of modifications.

To achieve the EPA regulations with the basic Modified Conventional Combustor while maintaining the traditional performance requirements listed in the introduction is a major challenge to the combustion designer. Further emission reduction requirements would certainly require adoption of the Advanced Low Emission Combustor discussed in Sec. V.

## V. Advanced Low Emission Combustor

A variety of conventional combustor modifications that mainly produced CO-$NO_x$ trades were discussed in Sec. IV. The maximum simultaneous CO-$NO_x$ emission reduction obtained was about 50%. The conventional combustor is limited in emission reduction potential by the basic conventional combustion process, which involves combustion of a droplet field. This is a heterogeneous/diffusion process characterized by regions of high combustion temperatures around each fuel droplet regardless of the over-all primary equivalence ratio. A second problem is local primary zone hot spots. The locally high temperatures give high $NO_x$ formation that can not be controlled.

To achieve lower emissions than obtainable from Modified Conventional Combustors, DDA has tested a variety of combustors employing the following sequence of events. 1) Premix the liquid fuel (JP-4) with all combustion air. 2) Prevaporize the fuel prior to combustion. 3) Burn the resulting mixture. This sequence avoids the conventional heterogeneous droplet combustion process and its associated emissions limitations. Experimental emission results from this Advanced Low Emission Combustor class are shown in Fig. 7. The movement of the CO-$NO_x$ curve toward the origin indicates an emission technology advancement with a simultaneous CO-$NO_x$ reduction. This combustor class has demonstrated greater than 90% emission reduction.

Typical Advanced Low Emission Combustors UHC results are shown in Fig. 8. For this combustor class the UHC standards are more easily achieved than the CO standard. The CO is thus the limiting constituent. Smoke emission from the Advanced Low Emission Combustors was below the measurable range. Visually, combustion occurs with a blue or transparent flame with no yellow, indicating no fuel breakdown to carbon.

$NO_x$ emission from the Low Emission Combustors correlates remarkably well with analytical predictions, Fig. 9. The DDA reaction model has 18 reactions plus a "global" HC fuel breakdown reaction. The 18 reactions were chosen for their effect on computed results over a wide range of gas turbine operating conditions. The excellent agreement with computed results is probably due to the predictable nature of the low emission combustion process which occurs essentially at one homogeneous condition and without hot and cold spots. Figure 9 indicates that burner outlet temperature can limit the attainable $NO_x$ emissions. The low emissions technology presented in this section has been demonstrated on single can combustion systems at relatively high inlet temperature (1000°F), low pressure (4 atm) and low heat release rates (3–5 × $10^6$ BTU/hr $ft^3$ atm). These conditions are representative of an SST operating at high Mach number high-altitude cruise. Extensive research and development must be accomplished before such results could be demonstrated in a modern annular aircraft combustor operating over the required LTO duty cycle. A potential Advanced Low Emission Annular Combustor is shown schematically in Fig. 10. The main potential problems of such a combustion system are:

1) The Advanced Low Emission Combustor may be appreciably larger than current combustors. CO consumption is improved by increased size. Increased size increases $NO_x$ emissions, however. Reduced loading appears to improve the over-all tradeoff.

2) Variable geometry of some type is a definite requirement to maintain ultra low emissions over the operating range. This is obviously accompanied by increased control complexity and cost.

3) Variable geometry compensation is also required for flame stability over the operating range.

4) A pilot fuel system may be required to obtain adequate ignition and relight capabilities.

5) Fuel vaporization is a problem at low inlet temperature. Solutions to this problem result in complex and costly designs.

6) Future engines may have limited turbine inlet temperature and possibly a limited cycle-pressure ratio as a result of more stringent emission control. Such restrictions would reduce SFC performance.

Balancing these problem areas is 90% simultaneous CO-$NO_x$ emission reduction. Other advantages for the Advanced Low Emission Combustor are: 1) No turbine erosion from carbon particles. 2) Improved turbine inlet temperature pattern due to elimination of hot zones, achieved with premix systems. 3) Reduced radiation, which reduces combustor cooling requirements and increases durability. 4) More amenability to analysis than the conventional combustor. After the basic design technology is established, this will lead to greatly reduced development requirements.

## VI. Conclusions

Recently issued EPA aircraft emission regulations will have a great influence on future combustor designs. Compliance with existing regulations can probably be achieved with modifications to conventional combustion systems. These modifications include airblast fuel preparation, optimized reaction volume, and possibly variable airflow fuel staging, or idle bleed. These types of changes optimize emissions from the conventional droplet combustion process. A major challenge is to retain the traditional combustor virtues in the modified designs.

Emission reductions of 90% can be made by abandoning the conventional droplet combustion process in favor of premixed-prevaporized combustion. Basic feasibility has been demonstrated in single can combustors. A major combustion challenge is to incorporate this Advanced Low Emission Combustor technology into annular aircraft combustors which also satisfy the traditional combustor requirements.

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# P³G—A New Dynamic Distortion Generator

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**A Planar Pressure Pulse Generator ($P^3G$) was developed for use in quantitative evaluations of compression system response to large sinusoidal pressure oscillations over wide ranges of frequency. The $P^3G$ is a mechanical device consisting of coaxial rotors and a stator with matched holes. Frequency of the generated pulses is controlled by rotor speed, and amplitude is controlled by varying axial rotor-to-stator spacing. Secondary flow is not required since the $P^3G$ operates on compressor or engine airflow. Test data substantiate that the $P^3G$ produces the following results. 1) High enough peak to peak amplitude discrete frequency pressure oscillations over the range of 40 to 800 Hz for use in compressor or engine stability testing. 2) Enough variation and control of peak to peak amplitude and frequency to obtain parametric data on compressor or engine surge characteristics. 3) Good sinusoidal waveform characteristics which generally exhibit harmonics of less than 20% of the fundamental amplitude. 4) Good wave planarity as measured by similarity of ring and rake peak to peak pressure amplitudes and phase.**

## I. Introduction

MOST engine stability testing to date which addresses the effects of dynamic inlet distortion has been based on combined spatial and temporal distortions as typified in Fig. 1.

While such approaches can be quite representative of aircraft inlet environments, quantitative understanding of the engine response to the dynamic phenomena may be limited by the complexity of these combined distortions.

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