The Development of Quiet Jet Engine Technology

Summer 1979

Bradley D. Beck

University of Central Florida

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ABSTRACT

The physical properties and subjective characteristics of sound and several special methods of measuring sound levels are discussed in order to provide a basic understanding of sound in general and noise in particular. The Federal Aviation Administration's regulation, FAR 36, which stipulates the allowable perceived noise levels produced by commercial jet aircraft, is examined in detail. The principle of jet propulsion, the basic components of turbojet and turbofan engines, the theory of aerodynamic sound and the origin of the perceived noise decibel (which is the basic unit for measuring aircraft noise) are presented to provide an understanding of the fundamentals of jet aircraft noise. The origin of the jet noise problem is traced to the introduction of commercial jet aircraft in 1958. The sources of jet engine noise, their generating mechanisms and the applications of acoustic design technology incorporated to reduce the various components of jet engine noise are identified for each generation of jet engines powering subsonic commercial jet aircraft: turbojet, low bypass ratio turbofan and high bypass ratio turbofan engines. The technique used to identify a source of jet engine noise, specifically compressor noise, is demonstrated by presenting the spectral analysis (obtained by
utilizing Fast Fourier Transform Software) of noise produced by a single stage axial flow fan rig. A review of airport noise, due to jet aircraft approaches and takeoffs, throughout the history of commercial jet aircraft, demonstrates the progress the aircraft industry has made in reducing the noise produced by jet engines powering commercial jet aircraft.
ACKNOWLEDGEMENTS

To my wife, Ginger, for her continued support and assistance.

To Mr. E. B. Smith, for providing insight into the source generating mechanisms of compressor and fan noise and for helping to formulate a macroscopic view of the development of jet engine acoustic technology.

To General Electric Company, for providing illustrative material contained in this text.
THE DEVELOPMENT OF QUIET JET ENGINE TECHNOLOGY

BY

BRADLEY D. BECK
B.S.A.E., University of Cincinnati, 1970

RESEARCH REPORT

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of the College of Engineering at the University of Central Florida, Orlando, Florida

Summer Quarter
1979
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CHAPTER 1

THE NATURE OF SOUND AND HOW IT AFFECTS HUMANS

1.1 What is Sound?

1.1.1 General Description and Classifications

Sound can be defined as that phenomenon which stimulates the human ear and brain to perceive the sensation of hearing. Sound is one of the ways that humans can communicate with each other and their environment. Although sounds can be transmitted through solids, liquids and gases we are generally interested in the propagation of sound through air where the sounds are characterized by variations of air pressure about the mean atmospheric pressure.

Almost all important natural sounds can be grouped into three classifications: speech, music and noise (Kinsler and Frey 1962). Speech is the sound produced by a human voice. Music is defined as any sweet, pleasing or harmonious sound. Noise, which is the topic of this paper, is defined as any sound that is unpleasant or contains no useful information. As seen from their definitions both music and noise are subjective phenomena that can only be judged by the listener.
1.1.2 Physical Properties of Sounds

1.1.2.1 Sound Pressure Level

All sounds can be represented by their sound pressure level (SPL) and frequency. The sound pressure level, measured in units of decibels, is defined as:

$$\text{SPL} = 20 \log_{10} \frac{P}{P_R}$$

where: $P = \text{root mean square sound pressure to be represented}$

$P_R = \text{reference pressure which is usually .0002 microbar}$

The decibel is a convenient scale to use because of the wide range of pressures which the human ear can withstand and also it is a realistic scale since the human ear does not respond in a linear fashion. The reference pressure corresponds to a sound which represents the threshold of hearing at a frequency of 1000 Hz. The threshold of pain is experienced at a pressure of 2000 microbars (140 dB).

Therefore the ear can distinguish sounds produced by pressures over a range of $10^7$ times the reference pressure. Figure 1 lists a few common noise sources and their corresponding sound pressure levels (Ventre 1974).
<table>
<thead>
<tr>
<th>Sound Pressure (microbars)</th>
<th>Sound Pressure Level (db)</th>
<th>Sound or Effect of Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>140</td>
<td>Threshold of pain</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>Unsuppressed exhaust from turbojet engine at angle of max intensity at 150 ft.</td>
</tr>
<tr>
<td></td>
<td>124</td>
<td>Suppressed exhaust from turbojet engine at angle of max intensity at 150 ft.</td>
</tr>
<tr>
<td>200</td>
<td>120</td>
<td>Loud automobile horn</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>Noisy factory</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>Passing truck</td>
</tr>
<tr>
<td>.2</td>
<td>60</td>
<td>Conversational speech</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>Residential area--day</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>Residential area--night</td>
</tr>
<tr>
<td>.002</td>
<td>20</td>
<td>Rustle of leaves</td>
</tr>
<tr>
<td>.0002</td>
<td>0</td>
<td>Threshold of hearing</td>
</tr>
</tbody>
</table>

FIGURE 1. Common Sources of Noise.
1.1.3 Subjective Characteristics of Sound

1.1.3.1 Loudness Level

In addition to the physical properties mentioned previously, continuous sounds can be distinguished by three subjective characteristics: loudness, pitch and timbre. Loudness levels are determined by comparing various pure tones to a reference pure tone (usually 1000 Hz) at a known intensity. The intensity of the measured tone is adjusted until it sounds as loud as the referenced frequency in decibels. Figure 2 illustrates equal loudness contours.

1.1.3.2 Pitch

Pitch is commonly thought of in reference to the sound produced by a musical instrument or a singer's voice. While it is primarily dependent on frequency it is also a function of intensity and wave form.

1.1.3.3 Timbre

Timbre is also usually associated with the sound produced by musical instruments and it is that quality which allows us to distinguish the sounds from different instruments even when they produce the same note with equal loudness (Kinsler and Frey 1962).
FIGURE 2. Equal Loudness Contours.
1.1.4 Commonly Used Measures of Sound

1.1.4.1 General

There are several special methods of measuring sound which provide information about the intensity or annoyance levels of a sound but do not actually indicate its physical properties. This is especially true with aircraft noise measurements. There are also common divisions of the frequency domain for the purposes of spectral analysis. Some of these special acoustic tools will be discussed in the following paragraphs.

1.1.4.2 Sound Level and Weighting Networks

Several frequency weighting networks have been developed which attempt to provide objective measures of sound levels in the same manner that the human auditory system does. The most common scales employed are the A, B, and C scales which are essentially inverses of various equal loudness contours. The A and B scales attenuate the low frequency sounds (below 500 Hz) to a much greater extent than the C scale. All three scales attenuate sounds above 5000 Hz.

Each of these scales have been incorporated electronically in sound level meters and provide an objective measure of the overall loudness of sounds in decibels. It should be noted that sound level is not equivalent to sound pressure level (Ventre 1974).
1.1.4.3 Perceived Noise Level

The perceived noise level is used in the measurement of aircraft noise and provides a subjective measure of the flyover noise of aircraft in perceived noise decibels (PN\text{db}). Again this is not equivalent to sound pressure level. The method for computing perceived noise levels is based on psychoacoustic testing and will be discussed in greater detail in Chapter 3.

1.1.4.4 Effective Perceived Noise Level

This is basically a modification to the perceived noise level system which accounts for the duration of aircraft flyover time and also for the presence of pure tones. It was found that the perceived noise level system did not adequately represent noises spiked with pure tones such as those due to compressor or fan whines (Little 1961). Therefore, effective perceived noise level provides yet another subjective measure of noise and is given in units of effective perceived noise decibels (EPN\text{db}).

1.1.4.5 Frequency Analysis

It is important to know the spectral distribution of sound, particularly noise, for two reasons. First, the effects of noise on humans are a function of frequency. Specifically, it has been shown through testing that humans
are more annoyed by high frequency sounds. Secondly, it is important to know the frequency distributions of noise so that the sources of the noise can be identified. An example of this would be noise produced at the blade passing frequency of a jet engine fan or compressor.

In aircraft noise work, octave band or one-third octave band analyzers are utilized. These both employ constant percentage bandwidth filters which have a pass band or "window" which is always a constant percentage of the center band frequency. For octave band filters this is seventy percent and for one-third band filters it is twenty-three percent. Also, in octave bands the upper frequency limit is twice the lower frequency limit. The standard octave bands are presented in Figure 3 (Ventre 1974).

1.2 Human Auditory System

The human ear is indeed a phenomenal organ. It allows us to distinguish over 400,000 different sounds and, as stated above, responds to pressures of an extremely wide range (Vander, Sherman and Luciano 1970). Those pressures which produce sounds at the threshold of hearing result in displacements of the tympanic membrane (eardrum) on the order of $10^{-9}$ cm which is less than the diameter of a hydrogen molecule (Kinsler and Frey 1962).
<table>
<thead>
<tr>
<th>Lower Frequency (Hz)</th>
<th>Center Frequency (Hz)</th>
<th>Upper Frequency (Hz)</th>
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<tr>
<td>11.2</td>
<td>16</td>
<td>22.4</td>
</tr>
<tr>
<td>22.4</td>
<td>31.5</td>
<td>44.7</td>
</tr>
<tr>
<td>44.7</td>
<td>63</td>
<td>89.2</td>
</tr>
<tr>
<td>89.2</td>
<td>125</td>
<td>178</td>
</tr>
<tr>
<td>178</td>
<td>250</td>
<td>355</td>
</tr>
<tr>
<td>355</td>
<td>500</td>
<td>709</td>
</tr>
<tr>
<td>709</td>
<td>1,000</td>
<td>1,410</td>
</tr>
<tr>
<td>1,410</td>
<td>2,000</td>
<td>2,820</td>
</tr>
<tr>
<td>2,820</td>
<td>4,000</td>
<td>5,630</td>
</tr>
<tr>
<td>5,630</td>
<td>8,000</td>
<td>11,200</td>
</tr>
<tr>
<td>11,200</td>
<td>16,000</td>
<td>22,400</td>
</tr>
</tbody>
</table>

FIGURE 3. Standard Octave Bands
1.3 Effects of Sound on Humans

Sound in its various forms produces a wide range of responses in humans which vary from extreme pleasure to extreme irritability. Musical sounds can be very soothing and enjoyable to the listener. Sounds can also produce a sense of security or familiarity. For instance, a record reproducing the sounds of a woman's heartbeat and the sloshing sounds of fluid in the womb can help to comfort a newborn infant. Other sounds which provide a feeling of security are those which are common to one's environment.

Noise, on the other hand, can produce undesirable responses in humans. Noise is considered to be a stressor and can produce adverse physiological as well as psychological responses in people. Examples of physiological affects which are possible are: constriction of blood vessels, tensing of muscles, adrenal hormone injection and loss of hearing. Loss of hearing may be in the form of conduction deafness or nerve deafness among others. In addition to producing extreme annoyance noise can also interfere with speech communications and constitute safety hazards (Ventre 1974).
CHAPTER 2

NOISE REGULATIONS

2.1 General

As shown in the preceding chapter, noise can be very damaging to humans and their environment. Since it is part of the charter of any government to protect its citizens, various government agencies have instituted regulations to protect their constituents from noise. This includes federal as well as local governments. Those regulations put forth by the Occupational Safety and Health Administration (OSHA) and the Federal Aviation Administration (FAA) are particularly interesting. It should also be noted that private industry has imposed its own regulations which in some cases are more severe than those imposed by government agencies.

2.2 OSHA Noise Regulations

OSHA regulations pertain to a broad range of subjects which affect practically all industries and are voluminous in content. This paper will not examine any of them in detail (even those which apply to noise) but it is
worth discussing their table of allowable noise exposure
as this has had a substantial impact on the operations of
many private industries. This table is shown in Figure 4.
It lists the allowable exposure time of people to noise as
a function of the sound level as measured on the dbA
scale and does not allow any exposure to noises with sound
levels greater than 115 dbA.

2.3 FAA/FAR 36

Since the topic of this paper is concerned with jet
gas engine noise it is of particular interest to discuss the
noise regulation of the governing agency of commercial and
private air transportation—-the FAA. The FAA's current
standard on noise regulation is Federal Aviation Regulation
(FAR) 36 (Federal Aviation Administration 1978). This
document is very detailed and specific in nature and in
addition to containing various noise limits, it specifies
the type of instrumentation to be used in obtaining air-
craft flyover data and the methods to be used in computing
the subjective measures of sound which it refers to—PNdb
and EPNdb. Since all commercial aircraft must be certified
by the FAA they must adhere to the noise limits as stated
in FAR 36.

The noise limit for small propeller driven air-
craft are given in units of dbA, while those for commercial
<table>
<thead>
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<th>Continuous Exposure in Hours per Day</th>
<th>Noise Level dbA</th>
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<tr>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>92</td>
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<tr>
<td>4</td>
<td>95</td>
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<tr>
<td>3</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>102</td>
</tr>
<tr>
<td>1</td>
<td>105</td>
</tr>
<tr>
<td>.5</td>
<td>110</td>
</tr>
<tr>
<td>.25 or less</td>
<td>115</td>
</tr>
</tbody>
</table>

FIGURE 4. Allowable Noise Limits as Specified by OSHA
aircraft powered by turbojet and turbofan engines are in stated units of EPNdb. The effective perceived noise level is a subjective measure of noise (as discussed in Chapter 1). Various noise limits are stated which are a function of the following parameters.

a. Engine bypass ratio— with division occurring for engines with ratios equal to or greater than 2 and those with ratios less than 2.

b. Date of application for certification— with significant periods being prior to January 1, 1967: between January 1, 1967 and November 5, 1975; after November 5, 1975.

c. Aircraft mission segment— takeoff and approach.

d. Aircraft gross weight— with 600,000 lbs and 850,000 lbs representing significant divisions.

e. Number of engines— division occurring for aircraft with more than 3, less than 3 or exactly 3 engines.

Due to the number of parameters involved it is not worth listing all of the various noise limits. However, for purposes of illustration, the limit for an aircraft having three turbofan engines with bypass ratios greater than 2, a gross weight over 850,000 lbs and which was certified after November 5, 1975 is 104 EPNdb at takeoff.

2.4 Local Noise Regulations

Community noise ordinances are not recent innovations. Most people have been familiar with the concept of disturbing the peace for some time. However, in many instances these ordinances have been vaguely constructed
and ineffective. Recently communities have adopted ordinances which incorporate greater acoustic sophistication and specify allowable noise limits which are based on ambient noise levels in the community during various time periods.

An example of a model community noise ordinance as proposed by the Florida Department of Environmental Regulation in 1975, is given in the referenced literature. As stated in that document, providing a noise ordinance is only one step in obtaining noise control. Enforcement of the regulations set forth requires a staff of qualified personnel and acoustic equipment.

2.5 Legal Precedent: Jet Engine Noise Nuisance Damages Awarded

The National Law Journal recently reported (3/19/79) a very important decision affecting the commercial aviation industry. An appellate court in California upheld a judgement which awarded $86,800 to fifteen Los Angeles families who suffered emotional and mental distress from the nuisance of jet noise from nearby Los Angeles International Airport (Work 1979). The plaintiff's lawyer said it was the first ruling of its kind in the country.

The damages which were awarded on the basis of nuisance were only part of the settlement given to
homeowners in the proximity of the two north runways of the airport. In 1967, which was the year that the jet engine operations began at the airport, a group of six hundred people filed suit against the city and in 1975 awards of $896,000 were given for direct and inverse condemnation.

In the nuisance case, the plaintiffs' lawyer argued that the authorization to operate the airport is based on the assumption that it will operate in a non-tortious manner. The plaintiffs were required to testify about the annoyance, mental strain, worry, anger, frustration, nervousness and fear caused by the jet aircraft noise. They complained that the noise interfered with their sleep, talking, radio and television, use of the outdoors portion of their homes and entertainment of their friends.

It can be seen that judgements such as the one previously discussed provide economic impetus for the control and reduction of jet aircraft noise.
CHAPTER 3

JET ENGINE EXHAUST NOISE

3.1 Origin of Jet Engine Noise Problem

The introduction of commercial jet airliners in October, 1958 officially propelled the United States into the age of commercial jet aviation and simultaneously the age of jet engine noise. Original passenger service was that provided by Boeing 707 and British Comet 4 aircraft between New York and Europe (Beranek, Kryter and Miller 1959a). Prior to the introduction of commercial jet aircraft, the predominant sources of aircraft noise were the propellers of piston engine aircraft.

During the 1950's noise around airports increased steadily with increasing traffic and size of aircraft. With the introduction of heavy jet transports the very different quality of noise (compared to piston engines) highlighted the problem and the upward trend had to be halted (Greatrex and Bridge 1967).

Therefore, the advent of jet transports caused airframe manufacturers, aircraft engine manufacturers, and government agencies to address a problem which had not previously been a factor in aircraft design. This problem was the sound created by turbojet engines, since all of the original jet transports (such as the Convair 880 as well as those
mentioned previously) were powered by turbojet engines (Walley and Gardner 1960).

Jet engines had been in use for several years on military aircraft but this had not posed a widespread noise problem because military bases were usually located in isolated areas. On the contrary, commercial airports were usually located near large population centers—especially in the early years of commercial jet aviation.

Public agitation about the jet sound problem was based on experience with the military jets then flying; many of which used afterburners during take-off and climb-out. The fact that afterburners were extremely noisy devices which would not be used on the jet transports was generally ignored. However, this military experience, plus the greater proximity of commercial airports to population centers and the greater frequency of commercial transport take-offs made it abundantly clear that some method of suppressing jet sound would be necessary (Walley and Gardner 1960).

The solution of the jet engine noise problem posed serious challenges for the designers of the next jet airliners (Smith 1959). Before proceeding further with an elaboration of the specific nature of the jet noise problem, it seems prudent to discuss the nature of jet engines in general and turbojets and turbofans in particular.

3.2 Principle of Jet Propulsion and Jet Engine Components

3.2.1 Operating Principle

The principle of jet propulsion is derived from an application of Sir Isaac Newton's laws of motion. A force
is required to accelerate a fluid or impart a change of momentum to the fluid. When this occurs there is an equal and opposite reaction force. It is this reaction force, of the working fluid in a jet engine, exerted on the engine, which is called thrust. Therefore, the principle of jet propulsion is based on the reaction principle. Even the propellers of the reciprocating piston engines obey the same principle as the momentum of the fluid (air) is changed (Hesse and Mumford 1964). However, there are striking differences between piston engines and jet engines and these can best be described by discussing the method of energy transfer between the working fluid and the engine itself.

In reciprocating machines, the process is one of positive displacement, with a fixed amount of working fluid being positively contained during its passage through the machine, and undergoing changes of pressure by means of variation in the volume of the container, that is, the fluid is caused to change its state by means of a moving boundary (Shepherd 1956). However, in jet engines, the fluid is not contained but rather is in a steady flow through the engine. Also, the types of jet engines this paper will deal with (principally turbojets and turbofans) create changes of pressure in the fluid primarily by means of dynamic effects from rotating parts. It should be noted that some jet engines (namely ramjets and pulse jets) do not contain rotating parts.

Devices utilizing the jet propulsion principle are divided into two classifications: air-breathing
engines and rocket engines. Air-breathing engines are so named because they utilize the air for their working fluid and they are further divided into the following types: (a) ramjet, (b) pulse jet, (c) turbojet, (d) turboprop and (e) turbofan. Commercial jet transports are principally turbojets and turbofans. Ramjets and pulse jets have no commercial applications and the numbers of turboprop transports are small in comparison.

3.2.2 Turbojets

The principal elements of a turbojet engine are illustrated schematically in Figure 5, and they are: diffuser, mechanical compressor, combustor, mechanical turbine and nozzle. The purpose of the diffuser is to transform the kinetic energy of the entering air into a static pressure rise. The mechanical compressor performs work on the air which raises the pressure of the air further. This high pressure air enters the combustion chamber where a continuous combustion process takes place as the result of jet fuel being mixed with the air. The high pressure, high temperature air then enters the turbine where it expands and does work on the turbine—providing the power to drive it. The turbine is mechanically coupled to the compressor and therefore, drives it. Hence, the function of the turbine is to extract energy from the working fluid and drive the mechanical compressor.
FIGURE 5. Principal Elements of a Turbojet Engine
Finally the gases enter the exhaust nozzle where they expand further and exit with a velocity which is greater than the velocity of the air at the engine entrance, thereby providing a thrust for propulsion.

An optional feature of a turbojet engine is an afterburner or augmentor. While these devices are not used on subsonic commercial transports, they are worth discussing. Since the materials of the turbine have limited operating temperatures, moderate amounts of fuel (as compared to that in a stoichiometric mixture) are burned in the combustor. Therefore, the exhaust products downstream of the turbine can have considerable amounts of excess oxygen. Supplemental thrust can be obtained by installing an afterburner downstream of the turbine where additional fuel can be added and burned with the excess oxygen. This process increases the exit velocity of the air and hence the thrust of the engine (Hesse and Mumford 1964).

3.2.3 Turbofans
3.2.3.1 General

Turbofan engines contain the same basic core engine as turbojets. These core engine components function as described previously. In addition, as the name turbofan implies, a fan is added. There are two principal configurations for turbofans: one with the fan at the front
of the engine and the other with the fan at the rear of the engine. The method of driving the fan varies with configuration, but it is most commonly accomplished with the addition of a second turbine. There is a forward fan engine with three separate turbines and drive shafts (Pratt and Whitney Aircraft 1970).

The fan of turbofan engines is larger in diameter than the core or high pressure, compressor. Consequently, some of the air pumped by the fan does not pass through the core engine. This airflow, referred to as secondary airflow, is pumped down concentric fan or bypass ducts and exits around the core engine. The ratio of the secondary (fan) airflow to the primary (core) airflow is defined as the bypass ratio. This secondary airflow augments the engine's thrust and in fact can be the primary source of thrust in high bypass ratio turbofans. The thrust provided by the fan airflow is typically between 30 and 75 percent of the total engine thrust, with the value dependent on bypass ratio (Pratt and Whitney Aircraft 1970).

3.2.3.2 Aft Fan Turbofan

Figure 6 provides a schematic representation of an aft fan engine while Figure 7 shows a cutaway view of General Electric's CJ805-23 aft fan engine. The unique feature of aft fan engines is that the fan blades and the
FIGURE 6. Principal Elements of an Aft Fan Turbofan Engine
FIGURE 7. Cutaway View of General Electric's CJ805-23 Aft Fan Turbofan Engine
turbine vanes are combined in a single unit which rotates freely behind the core engine. A seal separates the fan airflow (on the outside) from the core airflow.

3.2.3.3 Forward Fan Turbofan

Figure 8 provides a schematic representation of a dual compressor forward fan engine, commonly used in modern aircraft. In this type of engine, the fan is an integral part of a low pressure compressor and is driven by a low pressure turbine located behind the high pressure turbine. The low pressure spool shaft passes inside the shaft linking the high pressure compressor and high pressure turbine. Figure 9 shows a cutaway view of a dual compressor forward fan engine--General Electric's CF6-50.

For purposes of completeness, it should be noted that Pratt and Whitney Aircraft's JT3D engine, which was one of the original turbofans, had only one turbine. In that engine, the first turbine stage drove the high pressure compressor while the remaining three stages provided the drive power for the fan and low pressure compressor (Hesse and Mumford 1964).

3.2.3.4 Bypass Airflow Thrust

Since it has been stated that turbofan engines augment the thrust of the core engine (or gas generator) by utilizing secondary airflow in bypass ducts, it is
FIGURE 8. Principal Elements of a Dual Compressor Forward Fan Turbofan Engine
FIGURE 9. Cutaway View of General Electric's CF6-50 Dual Compressor Forward Fan Turbofan Engine
important to examine why this is true. As stated pre-
viously, the thrust of an engine is equivalent to the
reaction force of the fluid acting on the engine. This
force is equal to the time rate of change of the fluid
momentum. It can be simply stated as the mass and velocity
product of the air at the entrance of the engine minus the
same product taken at the engine exit. Although the bypass
airflow exhaust velocity is less than the core velocity,
the bypass mass flow can be much greater than that of the
core (depending on the bypass ratio). It is for this
reason that the bypass flow can contribute significantly to
the total thrust of an engine and in fact provide the
majority of thrust for high bypass engines.

3.3 Jet Noise Regulations: Origins of
the Perceived Noise Decibel

The aircraft industry and government agencies
alike recognized the need to control the jet noise problem
in order to gain public acceptance of the new jet trans-
ports. The original goal of industry and government was
that the jet transports would not be "noisier" than the
existing piston engined aircraft. The term noisier was
a source of considerable confusion. It was a common error
of early acoustic analysis to compare the noise of jet
engine aircraft to that of piston engine aircraft by
comparing the overall sound pressure level in decibels.
This procedure was in error because noise is a subjective
phenomenon and must be treated as such. The human ear responds differently to equal intensity sounds of different frequencies, with higher frequency sounds causing greater irritation.

The Port of New York Authority played a key role in formulating and enforcing the first jet noise regulations. They employed the firm of Bolt, Beranek and Newman to evaluate the noise produced by a typical jet engine—compared to that produced by the larger piston engined transports. The firm of Bolt, Beranek and Newman have made major contributions in the area of jet aircraft noise starting in 1949 and continuing through the present. Their work with the Port of New York Authority involved psychoacoustic evaluation and statistical analysis of noise and led to the development of the perceived noise level (in units of PNdb) which became a landmark standard in comparing aircraft noise throughout the industry. Details of the method of evaluating aircraft noise using the perceived noise level were presented at the 1958 Meeting of the Acoustical Society of America and in part in the September, 1959 issue of *Noise Control* (Beranek, Kryter and Miller 1959b). Due to the widespread use of PNdb it is worthwhile to provide some detail of the implicit meaning of the term and the method of computing it.

The quantity, perceived noise level, expresses in a compact way the measure of "noisiness" that is implicit in a listener's reactions to the sounds of
aircraft and yet is measured on a scale that is roughly comparable to the more familiar scales of physically-measured noise levels (Beranek, Kryter and Miller 1959b).

Basically it utilizes humans as the recording instrument and thereby accounts for sound power as a function of the frequency spectrum of a sound. The scheme in computing PNdb is similar to that used in determining loudness levels. The key element to the process is weighting the various frequency ranges (octave bands) for a given pressure level based on the magnitude of the subjective "noisiness" to humans in units of noys. The weighting scheme was based on studies where humans judged the relative annoyance of pure tones and narrow bands of noise. Using that information, a table was constructed giving the subjective noisiness in noys as a function of sound pressure level and octave band.

Perceived noise levels of aircraft were then computed in the following manner: Tape recorders were placed under the flight path of the aircraft to be evaluated and sound pressure levels were recorded in each of the eight octave bands. From the magnetic tapes, peak sound pressure levels were extracted and converted to peak perceived noise levels utilizing empirical formulae. First, the sound pressure level in each octave band was converted to a noisiness level (in noys) using the table described previously. Then the total noisiness was computed as follows:
\[ N_T = N_M + 0.3 (\Sigma N - N_M) \]

where:
- \( N_T \) = total noisiness
- \( N_M \) = largest value of noisiness for any of the eight bands
- \( \Sigma N \) = Sum of the values of noisiness from all eight bands

Finally, the perceived noise level was computed as follows:

\[ PN_{db} = 40 + 33.3 \log_{10} N_T \]

The significance of using \( PN_{db} \) can be illustrated by a simple example. Suppose that two aircraft, one piston engine and one jet powered, produced noise which displayed equal overall sound pressure levels of 100 db but had different perceived noise levels--105 \( PN_{db} \) for the piston engined aircraft and 110 \( PN_{db} \) for the jet. Based on the overall sound pressures alone, the two aircraft would be judged to be equally noisy. However, when perceived noise level is considered, the jet aircraft would be deemed noisier.

As part of their work for the PNYA, Bolt, Beranek, and Newman presented statistical perceived noise level data for typical large gross weight piston engined airliners and for the Boeing 707-120 and Comet 4 jet airliners. Based on their studies the PNYA specified 112 \( PN_{db} \) as the maximum allowable noise under the flight path of any aircraft. This imposed severe operational restrictions on the jet aircraft. For instance, the larger
propeller aircraft had a PNdb of 112 at takeoff conditions and an altitude of 400 feet. The Boeing 707 and Comet 4 aircraft had takeoff PNdb of 112 at altitudes of 1200 feet. This led to alterations of flight operations for the jet aircraft, such as reduced thrust landings and exceeding minimum allowable altitudes over populated areas during takeoffs.

3.4 Theory of Aerodynamic Sound

3.4.1 General Information and Statement of Problem

Aerodynamic sound is that which is generated as a by-product of an airflow, as distinguished from those sounds which are produced by the vibration of solids. When instability fluctuations occur in low Reynolds number airflows, regular eddy patterns are formed which are responsible for sounds such as those produced in musical wind instruments. However, in high Reynolds number airflows, the same type of fluctuations produce irregular turbulent motions which are responsible for sounds such as the roar of the wind and the exhaust noise of jet engines (Lighthill 1952).

In order for acoustic engineers to effectively reduce the exhaust noise produced by turbojet engines, it was necessary to understand the noise generating mechanism, or in essence the theory of aerodynamic noise. As with the advancement of any science, many people contribute towards its development. However, it appears that one man,
M. J. Lighthill, can be identified as making the most significant contribution towards the formulation of the theory of aerodynamic noise—at least as far as applications towards jet engine noise control are concerned. This conclusion is based on a review of the literature on jet engine noise during the late 1950's and early 1960's which contains many references to Lighthill's work in general and the Lighthill parameter in particular. He formulated a method for estimating the sound radiated from a fluctuating fluid flow which showed that total acoustic power was approximately equal to:

\[
\rho_o U^8 a_o^{-5} l^2
\]  

(Lighthill parameter)

where,

- \( \rho_o \) = density of surrounding medium
- \( U \) = typical velocity of the fluid flow
- \( a_o \) = speed of sound of surrounding medium
- \( l \) = typical linear dimension of the flow

The designs of the original exhaust noise suppressors for commercial turbojet engines were based on the principle postulated by Lighthill. His theory was published in two volumes of the *Proceedings of the Royal Society of London* (Lighthill 1952, 1954). Due to its significance, the salient points of his theory will be discussed with respect to basic assumptions and approach employed and examination of physical phenomena involved. Details of
mathematical derivations used will not be discussed but are disclosed in the previously referenced literature for the interested reader.

The first of Lighthill's publications pertained to the estimation of the sound field of a generalized fluctuating fluid flow while the second focused on the sound field of a turbulent jet.

Most of the pressure fluctuations within an airflow are balanced by fluctuations of fluid accelerations. Lighthill was concerned with the portion of the energy which escapes from the flow as sound and also with its directional distribution. The fundamental problem was to define the mechanism of converting the kinetic energy of fluctuating shearing motions to the acoustic energy of fluctuating longitudinal motions.

Lighthill's approach assumed that the fluctuating fluid flow acted on a uniform acoustic medium at rest. It should also be noted that his theory was restricted to subsonic flows. By examining the momentum within a fixed region of space, he developed an expression for the external stress field (of the fluctuating fluid acting on the acoustic medium). This expression consisted of hydrostatic pressures, viscous stresses and Reynolds stresses, which are the rate at which momentum in one direction crosses a unit area in a perpendicular direction. Since a fluctuating force is equivalent to a dipole,
he deduced that a stress field, which produces equal and opposite forces on both sides of a small element of fluid, was equivalent to a quadrupole. Some physical insight to these acoustic quadrupoles can be gained by examining the analogous electric quadrupole. The electric quadrupole consists of two equal and opposite dipoles that do not coincide in space so that their electric effects at distant points do not quite cancel. The electric dipole consists of equal and opposite point charges, which are separated in space and create an electric potential (volts) at distant points (Haliday and Resnick 1965). Therefore, the electric quadrupole consists of dipoles which create an electric potential field whereas the acoustic quadrupole consists of small elements of fluid with fluctuating stress field acting on them which create an acoustic potential (or sound radiation) field.

3.4.2 Formulation of Mathematical Model

The problem that Lighthill solved was to obtain a mathematical solution to the radiation field created by a distribution of acoustic quadrupoles. He found that resolving the stress field into a pressure and a single pure shearing stress allowed him to represent the field by three mutually orthogonal longitudinal quadrupoles and one lateral quadrupole (where longitudinal and lateral refer to the orientation of the quadrupole axes). This led to
splitting the sound field into two constituents: a source field (of strength proportional to stress tensor) due to the applied fluctuating pressures and a field of lateral quadrupoles due to applied fluctuating shearing stresses (fluctuating Reynolds stresses and viscous stresses).

3.4.3 Dimensional Analysis

Application of dimensional analysis led to the Lighthill parameter (discussed previously) which yields an expression for the total acoustic power of a fluctuating fluid. It is important to note that this analysis included considerations of the Stokes effect. Basically, this states that generating sound aerodynamically is the least efficient means of converting kinetic energy to acoustic energy and that this is particularly true as the frequency is decreased, or as the wave length of the sound is increased. The physical explanation for this is that any forcing motion which is comparable in scale with the wave length is balanced in part by a local reciprocating motion (standing wave) and in part by compressions and rarefactions of the air whose effect is propagated outwards. The larger the wave length of the sound (lower the frequency) as compared to the forcing motion, the more the motion is balanced by the local standing wave. This also provides additional physical insight for aerodynamic sound generation, in that it is the radiation due to the small fraction
of the fluctuation in momentum flux (Reynolds stresses) which are not balanced by a local reciprocating motion, that has to be determined.

3.4.4 Moving Reference Frame Modifications

Lighthill also modified his results to account for flow which is analyzed with respect to a moving frame; in particular, those flows produced by jet engines in aircraft. When this is accounted for, he found that there is an increased quantity of sound in directions making an acute angle with the direction of motion and a decreased quantity of sound in directions making an obtuse angle with the direction of sound; with preference for downstream emission. This preference is due to the eddy convection mach number or the speed at which aggregate volumes of air are propagated downstream.

3.4.5 Statistical Nature of Turbulence

In the second of Lighthill's publications, he expanded his theory to account for the statistical nature of turbulent jets and also to account for the results of many experiments conducted on the flow of cold jets. A good test of any theory is obviously comparison with experimental results and therefore, the significant conclusions of those tests are listed below:
1. Results verified that the total acoustic output was proportional to a high power of the jet velocity—near the eighth power as predicted.

2. The spectrum of the aerodynamic noise was very broad—on the order of seven octaves.

3. Almost all of the sound was radiated in directions making an acute angle with the jet axis.

4. The directional maximum for the higher frequency sound was at an angle of 45°, or slightly less, to the jet axis. The source of this high frequency sound appeared to emanate from an area near the jet orifice.

5. The lower frequency sound had a directional maximum at much smaller angles (less than 45°) and the angle decreased as the mach number of the jet increased.

3.4.6 Directional Characteristics of Noise

Lighthill accounted for the directional maximum of the high frequency noise in the following manner. He determined that a heavy mean shear, such as that occurring near the orifice of a jet, acts as an aerodynamic sounding board which amplifies the sound generated. The physical reason for this is that there can be much greater variations in momentum flux if there is a large mean momentum to oscillate by the turbulent fluctuations in velocity and also that there is a mean velocity to transport the turbulent fluctuations or momentum. This can be seen by examining the Reynolds stresses (momentum flux) which are expressed by $\rho V_x V_y$, or $(\rho V_x) (V_y)$. It can easily be seen that if a large mean velocity ($\bar{V}_y$) exists, that the results would be amplified. Also, he determined that the mean
shear tends to orient the majority of the quadrupoles along the principal axes of rate of strain which are at 45° to the direction of motion for a shearing action.

The fact that the low frequency noise has a directional maximum at angles much less than 45° can be explained as follows. In the core of the jet the effect of the mean shear is not nearly as great as near the jet orifice. Therefore, the sound field is a mixture of lateral quadrupole radiation (due to the interaction of the turbulence and the mean shear) and radiation due to turbulence alone (which is not as directional). When this is modified due to the eddy convection effect, the result is sound with directional maximum at angles much less than 45°.

3.4.7 Average Eddy Volumes

Another significant concept proposed in Lighthill's second publication was that of separate average eddy volumes. Due to the statistical nature of the turbulence, he proposed that separate volumes of air (or eddy volumes) transmitted their quadrupole radiation independently.

3.4.8 Lighthill Parameter: Final Form

Also, he determined that his accurate prediction for total acoustic power (Lighthill parameter) was somewhat fortuitous due to offsetting errors. Actually, due
to the eddy convection effect, the total acoustic power should be proportional to some higher power (than the 8th as predicted) of jet velocity but that some unexplained phenomena caused the actual results to be very close to those predicted using his parameter.

Finally, he modified his prediction parameter to account for flows which had densities different from the atmosphere, such as that of hot exhaust gases of jet engines so that:

\[
\text{total acoustic power} = \rho_1^2 \rho_o^{-1} U^8 a_o^{-5} d^2
\]

where:
- \( \rho_1 \) = density of fluctuating fluid
- \( \rho_o \) = atmospheric density
- \( U \) = velocity of fluid
- \( a_o \) = atmospheric speed of sound
- \( d \) = representative length in fluid such as jet orifice diameter.

3.5 Initial Industry Efforts to Reduce Jet Engine Noise

3.5.1 Statement of Problem

As stated previously in this chapter, it was abundantly clear to government agencies and airframe and engine manufacturers alike that some method of suppressing jet engine sound was required. Initially, the aircraft industry in general considered the jet engine exhaust noise (aerodynamic noise) to be the predominant problem.
Therefore, the imminent introduction of commercial jet aircraft precipitated the race for the jet engine exhaust sound suppressor (Walley and Gardner 1960).

The basic problem was to alter the exhaust jet mixing action with the ambient air such that shearing forces and turbulent fluctuations were reduced, thereby reducing the sound radiated. Additionally, this problem had to be solved without incurring significant performance penalties in the form of reduced thrust. Early work in this area included that done by Lilley and Greatrex (of Rolls Royce in England), American airframe companies such as Boeing, Convair and Douglas Aircraft and American engine manufacturers--Pratt and Whitney Aircraft and General Electric.

3.5.2 Operating Principle of Exhaust Sound Suppressors

The operating principle governing the design of these initial jet exhaust sound suppressors was to divide the primary jet exhaust streams into a number of small streams which promote quick mixing of the hot exhaust gases with the outside air and which also spread the mixed gases over a large area. This modification of the turbulence mixing pattern lowered the sound energy radiated (overall sound pressure level) and it also modified the frequency spectrum of the sound radiated (Gibbs and Howell 1959).
The frequency of the noise emitted was raised, which was beneficial in two ways. First, some of the noise was above the audible range of the human ear. Secondly, the high frequencies which were in the audible range (which are more annoying) were attenuated to a greater extent than the low frequency noise by atmospheric absorption.

3.5.3 Development of General Electric's Daisy Nozzle

The development of General Electric's exhaust sound suppressor for the CJ805-3 engine, which powered the Convair 880 aircraft, is selected here as representative of the aircraft industry's effort in reducing the exhaust noise from the first generation of commercial jet engines. Their work will be presented in some detail in order to gain a better appreciation of the scope of the problem.

General Electric started their program to develop a sound suppressor in late 1956. At that time very little data existed regarding the design parameters for a sound suppressor. However, Lighthill had already published his theory which explained the basic mechanism involved in generating aerodynamic noise (as discussed previously in this chapter).

General Electric initiated a major aeroacoustics research program which had the following objectives (Gordon 1961):
1. Develop acoustical and aerodynamic tools and techniques applicable to the development of sound suppressors.

2. Establish additional correlation between aerodynamic and acoustics pertaining to jet noise.

They also built extensive facilities which included:

1. Reverberation room capable of testing 1/5 scale model suppressors.

2. Thrust stand which could measure aerodynamic and acoustic data simultaneously.

3. Outdoor blowdown facility.

Finally, a major test program was conducted to evaluate a multitude of sound suppressor configurations. Preliminary design efforts included 1/5 scale model tests of over 100 different configurations. The configurations tested included the following types:

1. plug nozzles—with various combinations and angles of swirl vanes at various positions relative to the nozzle throat

2. slot nozzles—where jet was broken up into a series of radial slots

3. multiple jet nozzles

4. finger and flap nozzles

5. shrouds

6. concentric nozzles

7. corrugated nozzles

Based on the scale model tests and mechanical design considerations, five configurations were chosen for full-scale engine tests. When these tests were completed a corrugated nozzle with eight lobes and a
centerbody plug was chosen as the best overall sound suppressor because of its good noise reduction characteristics and modest performance losses. This nozzle was identified as the Daisy nozzle due to its petaline configuration and is pictured as installed on the CJ805-3 engine in Figures 10 and 11 with an ejector shroud. This configuration (nozzle and shroud) was installed on the Convair 880 aircraft. The Daisy nozzle provided a reduction of 9db in overall sound pressure level and a reduction of 4 PNdb (at the angle of maximum sound intensity) with negligible performance losses.

After a substantial amount of flight test hours, Convair Aircraft concluded that the Convair 880 could meet the noise regulations imposed by the Port of New York Authority. Therefore, the Daisy nozzle was considered a success as the design intent was accomplished (Bertaux 1960).

3.5.4 Pratt and Whitney Suppressor

Pratt and Whitney Aircraft also developed an exhaust sound suppressor for the JT3C engine which powered the Boeing 707-120 aircraft. Their suppressor was a combination of the corrugated and multtube nozzle configurations as it contained a petaline center structure surrounded by eight individual tubes. This suppressor employed the same basic operating principle as the Daisy
FIGURE 10. Daisy Nozzle and Ejector Shroud Installed on General Electric's CJ805-3 Turbojet Engine
FIGURE 11. Closeup of Daisy Nozzle and Ejector Shroud on General Electric's CJ805-3 Turbojet Engine
nozzle (Pratt and Whitney Aircraft 1970).

3.5.5 Summary

The exhaust sound suppressors discussed in the preceding sections were effective in reducing the exhaust noise of the first generation of commercial jet engines. Consequently, the aircraft noise at takeoff was reduced. However, the approach noise caused by compressor whines remained a problem which will be discussed in the next chapter.
CHAPTER 4

COMPRESSOR NOISE

4.1 Origin of Problem

As discussed in the previous chapter, the aircraft industry originally considered jet exhaust noise to be the predominant source of aircraft noise. However, it soon became apparent that aircraft noise during airport approach, when exhaust noise was relatively low, was also creating substantial annoyance (Sharland 1964). The primary source of this annoyance was attributed to compressor noise, commonly referred to as compressor whine due to its characteristic high frequency. Research efforts in the late 1950's and early 1960's focused on a solution to this problem.

4.2 Identifying Source of Noise

4.2.1 General

How was it possible to substantiate the fact that the compressor was the primary source of approach noise? In general, how can one identify sources of noise produced by rotating parts? The answers to these questions can be obtained from a frequency analysis of the noise produced. Axial flow compressors produce broad band noise and also
tone noises which are present at discrete frequencies. The high frequency tone noises are of primary interest since they cause the greatest annoyance. It has been shown by Tyler and Sofrin (1962) and others that these tones are produced at the blade passing frequencies and their harmonics of the various stages of the compressor. Blade passing frequency is defined to be the number of blades in any given stage times the rotational speed of the rotor. The method of identifying a source of noise through frequency analysis will be demonstrated by examining the results of a scale model axial flow fan test.

4.2.2 Test Setup

Figure 12 provides a schematic representation of the referenced test, which was conducted in 1978 at General Electric's test facility in Schenectady, New York. The information about this test and the data from it are provided courtesy of General Electric Company. A scale model (of a turbofan engine) axial flow fan rig was installed in an anechoic chamber and driven to various test speeds by an electric motor. The test rig was a single stage fan 20 inches in diameter, which contained 44 blades and 84 exit guide vanes. No inlet guide vanes were installed. A Bruėl and Kjær sound microphone was positioned at a distance of 17 feet from the rig inlet centerline. The data which we will examine was obtained
FIGURE 12. Schematic of Axial Flow Fan Rig Test
at a fan speed of 8924 RPM. The blade passing frequency corresponding to this speed is:

\[(44 \text{ blades})(\frac{8924 \text{ rev}}{\text{min}})(\frac{1 \text{ min}}{60 \text{ sec}}) = 6544 \text{ cyc/sec} = 6544 \text{ Hz} \]

Therefore, if the fan is the source of noise, we would expect a spectral analysis of the noise to indicate the presence of a strong tone at 6544 Hz.

4.2.3 Frequency Analysis

The spectral analysis of the data from this test utilized a digital technique known as the Fast Fourier Transform (FFT). The classical approach to spectral analysis involves the use of the Fourier series or the Fourier transform. However, with the advent of modern high speed digital computers a digital approach to Fourier analysis, known as the Discrete Fourier Transform (DFT), was developed.

Use of the DFT allows any waveform, whether it is periodic or aperiodic, to be transformed from the time domain to the frequency domain. The mathematical expression of the DFT is shown below (Tektronix Inc. 1978):

\[X_d(k\Delta f) = \frac{1}{N\Delta t} \sum_{n=0}^{N-1} x(n\Delta t)e^{-j2\pi kn/N}\]

Where:  
\[t = \text{time}\]
\[T = \text{time interval of sampling}\]
\[X_d = \text{waveform amplitude in frequency domain}\]
\[ \Delta t = \text{time sample spacing} \]

\[ N = \text{number of samples in } T \]

\[ n = \text{time index} \]

\[ k = \text{frequency index} \]

\[ \Delta f = \text{frequency sample interval} = 1/T \]

The primary requirements for using the DFT is that the waveform be sampled in such a manner that the Nyquist sampling criterion is met. This criterion states that \( 1/(2\Delta t) \) be greater than the highest frequency in the waveform being sampled. Stated in another way, the highest frequency present must be sampled at least twice per cycle. This criterion must be met in order to prevent low frequency aliasing (foldover). Aliasing causes components to be represented at frequencies lower than those actually present.

The Fast Fourier Transform (FFT) is an algorithm which provides an efficient approach to evaluating the DFT. This algorithm takes advantage of the repeated terms and symmetry present in the evaluation of the DFT, which greatly reduces the number of computer operations required and consequently saves time and money. One requirement of using the FFT is that the number of samples, \( N \), is a power of two.

Figure 13 is a flow chart illustrating the basic steps in the analysis of our test data. The noise emitted
FIGURE 13. Flow Chart of Fan Noise Analysis
by the fan rig was received by the Brue! and Kjaer microphone, amplified and then recorded on magnetic tape. 

Next, a discriminator provided conversion to an electrical signal which was then passed through a 10 KHz anti-aliasing filter. After processing by an analog to digital converter, the time domain plots shown in Figures 14 and 15 were produced. Figure 14 shows the noise waveform over the entire time interval of .040 seconds while Figure 15 shows an expanded view of the first .004 seconds. Since the frequency range of interest for this data was 0-10,000 Hz (which is often the case in aircraft noise work) the required sampling rate to meet the Nyquist criterion was 20,000 samples per second (or greater). A rate of 25,600 was used in this case. The sample size employed was 1024 which is equivalent to 2 to the 10th power and therefore satisfies the requirements of the FFT.

The selection of the sample size may be a function of equipment limitations (computer memory) or of the required resolution (frequency bandwidth) of the analysis. For this example the frequency bandwidth is: 25,600 samples/sec/1024 sample = 25Hz. The sampling rate, sample size and bandwidth are interrelated and must be adjusted to satisfy the Nyquist criterion, the FFT criterion, and the desired resolution.

Returning to the flow chart of Figure 13, the digitized data was then operated on by FFT software
Instantaneous Peak Voltage (volts)

FIGURE 14. Fan Noise Versus Time

TIME TRACE OF CHANNEL A
FIGURE 15. Fan Noise Versus Time—Expanded View
contained in a digital computer (PDP 1135) in order to evaluate the DFT. Additional operations were then required to convert the complex integers obtained to real integers. At this point the frequency domain plot, which was the objective of this analysis, was produced. This frequency plot is shown in Figure 16.

4.2.4 Comparison of Results

In section 4.2.2 it was shown that the fan blade passing frequency for this test was 6544 Hz. Figure 16 shows the presence of a distinct tone at approximately 6600 Hz which is very close to the blade passing frequency. Therefore, it has been substantiated that the periodic pulsing produced from the fan blades is indeed the source of this noise.

4.2.5 Broad Application of FFT

The FFT is a very powerful tool which can be useful in a broad range of applications. Even within the narrow reference of jet engine analysis, its uses are varied. In addition to identifying fans, compressors and turbines as sources of noise, it can be used to identify mechanical problems. For instance, suppose that an accelerometer mounted on an engine casing indicated excessive engine vibrations. The signal from this accelerometer could then be analyzed, in the same manner as the noise
Relative Sound Pressure Level (db)

FIGURE 16. Spectral Analysis of Fan Noise
waveform, to identify probable sources of the vibration—such as a worn bearing rotating at engine speed.

4.3 Generating Mechanisms of Compressor Noise

4.3.1 General

Axial flow compressors on turbojet engines consist of a number of stages. Each stage has a cascade of stationary vanes (stator) followed by a row of rotor blades. Rotor-stator interactions play an important role in the generation of compressor noise.

4.3.2 Broad Band Noise

The broad band component of the compressor noise spectrum originates from two phenomena (Sharland 1964):

1. Random lift fluctuations on the rotor blades resulting from vortex shedding at the blade trailing edges.

2. Random lift fluctuations on the rotor blades due to upstream turbulence created by the inlet guide vanes.

4.3.3 Discrete Frequency Noise

4.3.3.1 General

Tyler and Sofrin (1962) wrote a definitive paper identifying the sources of discrete frequency noise in axial flow compressors. Their work was a result of a major research and development program conducted by Pratt and Whitney Aircraft. Their postulations, sometimes
referred to as the spinning mode theory, identified two sources of discrete tone noise: tones produced by rotors only and those caused by rotor-stator interaction.

4.3.3.2 Rotor Only

The principal sources of noise generated by the rotor are effects due to steady aerodynamic blade loading and to blade thickness. Let $B$ equal the number of rotor blades in any given stage. The blades are then spaced $2\pi/B$ radians apart and the associated pressure contours around the blades repeat in that interval. Hence, the presence of lobed pressure patterns. Since these patterns are associated with the rotor, they rotate at rotor speed $(N)$. The fundamental blade passing frequency, $BN$ Hz, is associated with a $B$-lobe pattern while the harmonics of the blade passing frequency $2BN$, $3BN$ Hz, etc., are associated with patterns having $2B$, $3B$, etc., lobes.

Experimental tests verified the presence of these lobed patterns and also that the rotor pressure field consisted of a superposition of these patterns.

The propagation of sound through various types of ducts was also studied. As a result of this, a critical or "cutoff" frequency was determined. This cutoff frequency in concentric cylindrical ducts (such as those in axial flow compressors) is a function of number of lobes in the pressure pattern and blade hub to tip ratio. For
driving frequencies (rotor speed) below cutoff, the pressure field decays exponentially in an axial direction from the rotor. Therefore, the discrete tones do not propagate out the front of the duct. For driving frequencies above "cutoff," the spinning lobed patterns propagate forward, exiting in a helical fashion. As the driving frequency increases above cutoff, the spiral angle changes—tending towards the duct centerline. This leads to the directional properties of compressor tone noise.

4.3.3.3 Rotor--Stator Interaction

The generating mechanisms of discrete frequency noise as a result of rotor-stator interaction are:

1. Cutting of wakes of upstream stators by rotor blades
2. Impingement of rotating blade wakes on downstream stators
3. Interruption of the rotating pressure field of the rotor by the proximity of reflecting objects, apart from wake effects.

Spinning lobed pressure patterns are also produced by the rotor-stator interaction. For each harmonic of the blade passing frequency, the interaction pressure field consists of a superposition of an infinite number of rotating lobed patterns. This is different than rotor only generated noise where only one pattern was responsible for the tones produced at each harmonic. The number of lobes in each pattern can be computed as follows:
\[ m = nB + KV \]

where:  
- \( m \) = number of lobes in the pattern  
- \( B \) = number of blades  
- \( V \) = number of vanes  
- \( n \) = positive integers, which determine the harmonics of blade passing frequency  
- \( K \) = all positive and negative integers

Each of the lobed patterns rotate at different speeds as is required to generate multiples of blade passing frequency.

Again, there is a cutoff rotor speed (for each lobed pattern) which separates pressure field decay from noise propagation. The concept of cutoff is very important. Through optimum selection of the number of blades, vanes and the rotor tip speed, the compressor can be designed such that the cutoff speed is above the operating speed of interest—such as airport approach speed.

4.4 Industry Efforts to Silence the Compressor

Extensive research and development programs conducted throughout the industry led to a greater understanding of the sources of compressor noise and consequently the knowledge required to reduce this noise. Some of the important compressor design parameters resulting from these programs are:
1. number of blades to number of vanes ratio
2. rotor-stator spacing
3. blade aerodynamic loading
4. blade tip speed
5. blade aspect ratio and solidity

A substantial portion of the information pertaining to the generation of compressor noise was gained after the introduction of the first commercial jet transports powered by turbojet engines. Consequently, the techniques for reducing aircraft approach noise, based on jet engine design, were not applied until subsequent generations of jet engines were developed. This will be discussed in the next chapter when noise produced by turbofan engines is reviewed.
5.1 Turbofans Versus Turbojets

Why were turbofan engines developed and what are their advantages as compared to turbojets? The answer to both of these questions is based on economic considerations. As the air transport market grew, demands for larger aircraft with more powerful engines were established. The design of these new powerplants required simultaneous consideration of several requirements, with the principal one being economy of operation (Kester and Slaiby 1967). The measure of economic operation for jet engines is specific fuel consumption, which is analogous to gas mileage for automobiles. Specific fuel consumption is a ratio of the fuel consumed in units of lbm/hr. to the thrust developed in units of lbf. The turbofan engines provided an economic solution to the demands of the marketplace since their specific fuel consumption was lower than that of turbojet engines under similar operating conditions (Hesse and Mumford 1964). Greatrex and Bridge (1967) showed that increasing the bypass ratio
decreased the specific fuel consumption and therefore provides more economic operation.

The original turbofans, or second generation of jet engines, were of the low bypass ratio (2 to 1 or less) type. Technology advances such as the concept of an air-cooled turbine design, allowed turbine operating temperatures to increase and precipitated the development of high bypass ratio engines such as the JT9D in the mid-1960's. Without increasing turbine operating temperatures, an increase in bypass ratio would result in performance deterioration (Kester and Slaiby 1967). Figure 17 lists a number of turbofan engines and their commercial applications. Two of the original turbojet engines are also listed for comparison of thrust levels.

5.2 Inherent Noise Characteristics of Turboprops

The general nature of turbofan engines was discussed in Chapter 3. As stated then, turbofans develop part of their thrust from secondary airflow which is accelerated by the engine fan. The fans of turbofan engines produce between 30 and 75 percent of the total engine thrust with the percentage determined by the bypass ratio (Pratt and Whitney Aircraft 1970). Compared to a turbojet engine, a turbofan obtains a given thrust from a higher mass flow with lower jet velocity. Since the exhaust aerodynamic noise is strongly dependent on jet velocity (reference
<table>
<thead>
<tr>
<th>Engine Designation</th>
<th>Manufacturer</th>
<th>Thrust lbs.</th>
<th>Bypass Ratio</th>
<th>Commercial Aircraft</th>
</tr>
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<tbody>
<tr>
<td><strong>A. Turbojets</strong></td>
<td></td>
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<td></td>
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<tr>
<td>1. JT3C</td>
<td>P &amp; WA</td>
<td>13,500</td>
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<td>B707-120, 720</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>DC-8-10</td>
</tr>
<tr>
<td>2. CJ805-3</td>
<td>GE</td>
<td>11,000</td>
<td>N/A</td>
<td>CV-880</td>
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<td><strong>B. Low Bypass Ratio Turbofans</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. JT3D</td>
<td>P &amp; WA</td>
<td>21,000</td>
<td>1.5:1</td>
<td>B707-120B, 320B,C, **</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>707-323C</td>
</tr>
<tr>
<td>2. CJ805-23</td>
<td>GE</td>
<td>16,100</td>
<td>1.5:1</td>
<td>CV990</td>
</tr>
<tr>
<td>3. JT8D</td>
<td>P &amp; WA</td>
<td>15,500</td>
<td>-</td>
<td>B727, 737**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DC-9</td>
</tr>
<tr>
<td><strong>C. High Bypass Ratio Turbofan</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. JT9D</td>
<td>P &amp; WA</td>
<td>47,000*</td>
<td>5:1</td>
<td>B747, DC-10-20**</td>
</tr>
<tr>
<td>2. CF6-6</td>
<td>GE</td>
<td>40,000*</td>
<td>6.3:1</td>
<td>DC-10-10</td>
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<tr>
<td>3. CF6-50</td>
<td>GE</td>
<td>50,000* class 6.3:1</td>
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<td>B747-300</td>
</tr>
</tbody>
</table>

*Does not reflect thrust rating improvements.
**Partial list of applications

FIGURE 17. Selected Turbofan Engines and Their Commercial Applications.
Lighthill parameter in Chapter 3) the turbofan produces less exhaust noise at a given thrust. Additionally, the turbofan has its main exhaust stream surrounded by a ring of much lower velocity air expelled by the fan. This ring of fan air serves to buffer the main exhaust stream and thereby reduces the overall shearing effect (General Electric 1970). Some turbofan engines with substantially greater thrust than the original turbojet engines actually produced less exhaust noise. This will be examined in greater detail later in this chapter.

One disadvantage of turbofan engines is the inherent increase in fan noise as compared to turbojet compressor noise. However, due to the nature of the source generating mechanisms, this noise can be controlled by optimizing the fan design. Additionally, this noise can be reduced by utilizing sound treatment panels.

5.3 Low Bypass Ratio Turbofans

5.3.1 Exhaust Noise

The early turbofan engines, such as the JT3D and CJ805-23 were low bypass ratio turbofans. These engines produce less exhaust noise than the original turbojet engines due to the effects mentioned in Section 5.2.

In fact, some of these engines were as quiet or quieter without exhaust suppression as the turbojets were with suppression. As an example of this, the unsuppressed
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CJ805-23 turbofan engine at full takeoff power produced the same noise level as the suppressed CJ805-3 turbojet engine at 65% power (Gordon 1961). Consequently, mechanical exhaust suppressors (such as those used on the turbojets), were not employed on these engines. It should also be pointed out that mechanical suppressors would not have been effective due to the low exhaust velocities of the low bypass ratio turbofans (Tyler 1966).

5.3.2 Fan Noise

Although the move from pure turbojets to low bypass ratio turbofans reduced exhaust noise, it raised aircraft approach noise which was produced by the turbofan fan and compressor (Air Transport Association of America 1972). The aircraft industry took steps to reduce this noise. For instance, Pratt and Whitney Aircraft developed Hush Kits, consisting of compressor parts, which were installed in the JT3D engines for the purpose of reducing compressor noise (Tyler 1966). Also, General Electric developed resonator type suppressors for installation in the exhaust nozzle of the CJ805-23 engine for the purpose of reducing the discrete frequency fan whine of that engine (Gordon 1961).

However, significant reductions in aircraft approach noise, reflecting fan noise reduction were not achieved until high bypass ratio engines, such as the JT9D and the CF6-6 were introduced. Some insight into the reason for
this fact, at least with respect to Pratt and Whitney engines, is provided by the following quote from Pratt and Whitney's Gorton:

The JT9D is the first engine that we've been able to start with a clean piece of paper and design with all the noise reduction features we desired. All our previous engines had been outgrowths of some military design, and considerably limited (Levin 1966).

As Levin pointed out these military engines were limited because of their mission-conscious disregard for noise.

5.4 High Bypass Ratio Turbofans

5.4.1 Noise Sources

Figure 18 is a cutaway view of General Electric's CF6-50 high bypass ratio, forward fan, turbofan engine. This figure demonstrates the primary sources of noise present in all high bypass ratio turbofans and they are (General Electric 1973):

1. Forward radiated fan noise produced by fan blade passing frequencies, harmonics and multiple pure tone noise.
2. Aft radiated fan noise produced by fan blade passing frequencies and harmonics.
3. Fan exhaust jet aerodynamic noise.
4. Low pressure turbine noise.
5. Core engine exhaust aerodynamic noise.

Secondary sources of noise include combustor noise and casing radiated noise.
Fan Exhaust Aerodynamic Noise
Forward Radiated Fan Noise
Aft Radiated Fan Noise
Core Exhaust Aerodynamic Noise
Low Pressure Turbine Noise

FIGURE 18. Sources of Turbofan Engine Noise
5.4.2 Acoustic Design for Noise Reduction

Figure 19 is a schematic representation of the same CF6-50 engine and it is used to highlight the acoustic design features incorporated in that engine. They are (General Electric 1972):

1. Low fan tip speed for low noise level generation
2. Absence of inlet guide vanes eliminating inlet wake generated noise
3. Large axial spacing between the fan blades and the outlet guide vanes to reduce intensity of downstream wake noise
4. Outlet guide vane to fan blade ratio, selected to reduce fan noise
5. Low exhaust velocities which reduce shearing between exhaust gases and surrounding air and therefore reduces aerodynamic noise
6. Resonator type noise suppression panels.

The numbers delineated above correspond to those shown in Figure 19, which illustrates the location of the various design features. Although specific noise reduction techniques vary somewhat with engine manufacturer and engine model, the design features discussed above illustrate basic techniques for reducing turbofan engine noise. For instance, Pratt and Whitney Aircraft's JT9D turbofan engine incorporated the same design concepts (Kester and Slaiby 1967).
FIGURE 19. Noise Reduction Technology Incorporated in General Electric's CF6-50 Turbofan Engine
These design concepts consist of two basic types:

1. Those which eliminate or reduce the strength of noise sources (example—elimination of fan inlet guide vanes)

2. Those which reduce the magnitude of sound after it is generated (resonator type suppression panels).

The design of the suppression panels incorporates the Helmholtz resonator principle and geometrical optimization of the resonators allows them to be tuned to filter discrete frequency tones and also to reduce broad noise.

The exhaust velocities of high bypass ratio turbofans are even lower than those of low bypass ratio turbofans. Consequently, the exhaust noise is lower and mechanical exhaust sound suppressors are not required. As Hochheiser (1969) explained:

In general, as bypass ratio is increased, the percentage of propulsive thrust developed by the core engine decreases as the energy in the engine is used for driving the fan rather than for direct momentum in the form of a mass-velocity product through the primary nozzle. As such, the effect of increasing bypass ratio is often to decrease jet noise.

5.5 Acoustic Design Balance

It is advantageous to maintain a balance of the various noise sources in an engine. For example, if the fan noise in a turbofan engine is dominant, it can mask the noise of other sources such as the turbine. However,
as fan noise is reduced and approaches the level of
turbine noise, the turbine noise becomes more important
and must also be reduced to reduce the overall noise
level produced by the engine.

In the next and final chapter of this paper, the
history of commercial jet engine noise will be reviewed.
This review will demonstrate the significant noise
reductions achieved through the utilization of turbofan
engines.
CHAPTER 6

SUMMARY

6.1 Selection of Topics

6.1.1 Subsonic vs. Supersonic Aircraft

This paper has excluded any discussion of the noise produced by jet engines powering supersonic aircraft. Although commercial supersonic transports are in use, they constitute a small percentage of commercial jet aviation traffic and were excluded for that reason.

6.1.2 Specific Engines Discussed

Throughout this paper, the noise characteristics and/or the acoustic design features of various jet engines have been discussed. All of the engines cited are the products of either Pratt and Whitney Aircraft or General Electric Company, which are the two major American jet engine manufacturers. There are other jet engine manufacturers, with a notable example being Rolls Royce Ltd. of England. The choice of engines discussed was based on availability of information.
6.2 Noise Reductions Achieved Since the Introduction of Commercial Jet Transports

Figures 20 and 21 illustrate the significant progress the aircraft industry has made in reducing the noise of its jet engine powered commercial transports. Figure 20 depicts the progress made in reducing airport sideline noise which is indicative of the trend in engine exhaust noise. Figure 21 demonstrates the progress in reducing airport approach noise and primarily reflects reduction in engine compressor or fan noise (Air Transport Association 1972). Approach and sideline are two of the required measuring stations for determining aircraft fly-over noise as specified in FAR 36.

Units of EPNdb (shown in Figures 20 and 21) are not equivalent to db. However, some insight into the magnitude of sound reduction accomplished, can be gained by noting that a reduction of just 3 dB corresponds to a reduction in sound power level of 50%, while a 10 dB decrease would correspond to a reduction in sound power level of approximately 90% (General Electric 1971).

6.3 Conclusions

The application of acoustic technology to the design and development of commercial jet engines, since
FIGURE 21. Review of Aircraft Approach Noise
their origin, and the development of the turbofan engine, have yielded dramatic reductions in the noise produced by commercial jet engines. Technology advances, such as those gained from the NASA Quiet Engine Program, indicate that even greater noise reductions will be realized in the future.
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