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**LA THÈSE A ÉTÉ
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Sound Simulation,
For Flight Simulation Systems

Antonios Antoniadis

A Thesis
in
The Department
of
Electrical Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering at
Concordia University
Montréal, Québec, Canada

JULY 1985



Antonios Antoniadis, 1985

ABSTRACT

Sound Simulation for Flight Simulation Systems

Antonios Antoniadis

Problems usually encountered in designing a sound system for flight simulators are flexibility, in creating specific sounds, and modularity of hardware. A completely software implementation would require a lot of computer time, whereas an analog system would be very difficult to tune and maintain.

In the project described in this thesis, an attempt is made to solve these problems by using both methods of implementation, while maintaining at the same time the hardware modularity and the software implementation of specific sounds.

The simulation of sounds with main frequency components above 1 KHz is done using dedicated hardware generators, and sounds with main frequency components below 1 KHz are generated by a microprocessor, all under the control of a sound simulation software package.

ACKNOWLEDGMENTS

I would like to express my gratitude to all the people who helped me to complete the present paper, and in particular Mr. Roger Nader, Sound group Leader CAE Electronics, for his moral support and his technical advices, and my professor, Dr. Nikitas Dimopoulos for his guidance and endurance.

Finally, I would like to thank all those whose absence or presence forced me to "sit down and do it".

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CHAPTER 1

1.1. INTRODUCTION

Present day technology has much to offer to the training of aircraft pilots. Flight Simulators have been transformed from simple and awkward analog-mechanical devices, to the perfection of a completely digitally controlled system. Motion of six degrees of freedom, accuracy of instrument indicators, high resolution graphics systems, training methods and lesson plans, and a fully simulated sonic environment, are just a few of their high selling points.

Aircraft simulation requires a continuous real-time solution of the equations of motion of the airplane along with all other relationships needed to allow the pilot to "fly" the simulator with sufficient realism. In the past, sound simulation was not considered to be as important as other systems. Lack of sound data, complexity of simulation and the fact that the sound is not as tangible as the other systems, had reduced it to a non-essential part of the whole simulation. Most instructors used to turn it completely off, or airline

companies did not pose any requirements on it.

Today the situation is different. The perfection of simulation of the other aircraft systems, as well as the advancement on the technology of various electroacoustic systems - dedicated sound chips and sound microgenerators, programmable sound generators - and the supply of information on aircraft sound data, changed the attitude towards the simulation of sound. [15] A sound system is considered not only important, but absolutely essential to the realism of simulation, and to the proper training of pilots.

1-2 PURPOSE AND THESIS PRESENTATION

In this thesis a complete sound simulation system is described with emphasis on the software aspect of simulation. The project has been completed at CAE Electronics. Flight simulation systems. The present chapter names the different aircraft parts that generate sounds, while in flight or during ground operations, that are considered important.

In Chapter 2, the various sound signals are classified according to their properties, and also a method of data acquisition and signal analysis are presented.

Chapter 3 based on the analysis results, defines a method of hardware implementation.

In Chapter 4 the appropriate software requirements are

described in conjunction with the previously defined hardware.

Chapter 5 presents the implementation in software. The thesis concludes with comments on the results of the simulation. Appendix A summarizes the various parameters used in the simulation program. Appendix B supplies information on the sound analysis instrumentation. Appendix C presents a sample derivation for the engine sound shapers.

1.3 AIRCRAFT PARTS THAT GENERATE SOUNDS

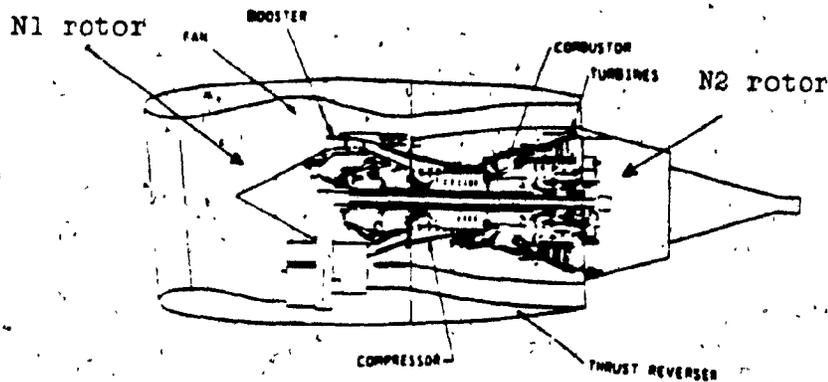
As a model of the simulation a Boeing 737 is considered. It is equipped with two engines and it is defined as a short to medium range aircraft. The different parts which are going to be considered as sound generators are:

- a. Engines
- b. Auxilliary Power Unit (APU)
- c. High lift devices
- d. Landing gear
- e. Air conditioning

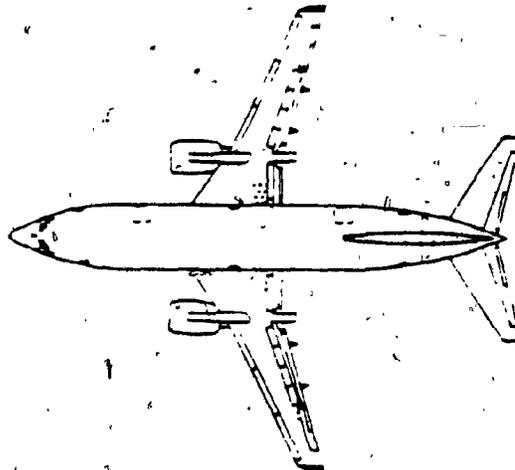
a. Engines

The aircraft is equipped with two high bypass turbofan engines rated at 20,000 pounds at takeoff thrust. The engine is a dual rotor assembly consisting of a fan rotor (N1) and a compressor rotor (N2). The N1 rotor consists of a single stage fan and a three stage booster section connected by a through shaft to a four stage low pressure turbine. The N2 rotor is a nine stage

axial flow compressor connected by a through shaft to a single stage high pressure turbine. The compressor delivers highly compressed air to the annular burner section of the engine, the combustor, where a fuel/air mixture is lighted by igniters. The resulting high energy gases enter the turbines, producing the power to drive the compressor and accessories as well as the fan at the front end of the engine. A fan exhaust reverser system is installed to deflect fan discharge air to aid in stopping the aircraft. [9]



*FIGURE 1.1 Engines *

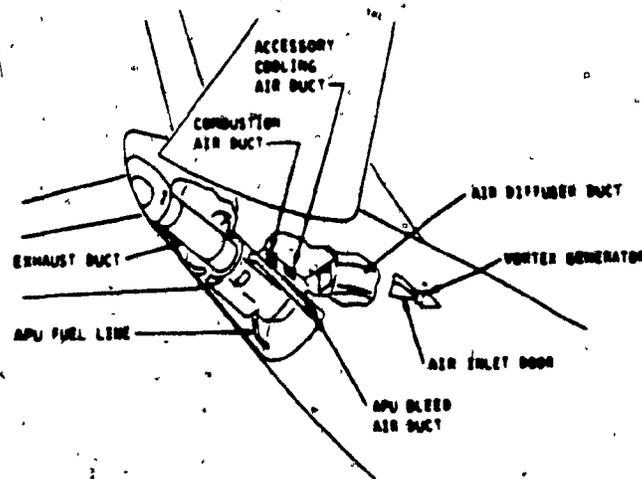


*FIGURE 1.2 Engines *

B. Auxilliary Power Unit

The APU's main function is to supply electric power and bleed air for engine ignition, while on ground and in the absence of any other ground power unit. During flight, in case of engine failure, it is used to restart the engine. It is a self-contained gas turbine engine. It is installed within a fire proof, sound reducing shroud located in the tail of the airplane. The APU consists of a two stage compressor, a turbine, and an accessory drive section. Gear driven units in the accessory drive control the APU from start to shutdown.

[8]



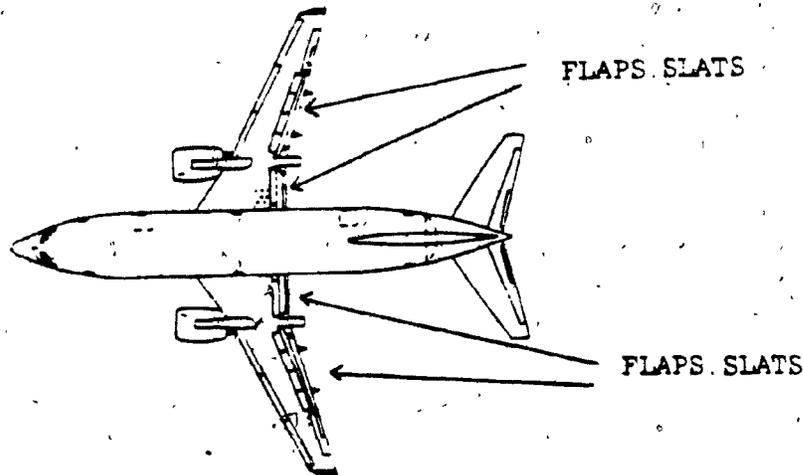
*FIGURE 1.3 APU *

c. High lift devices

High lift leading edge devices are used in combination with the trailing edge flaps to increase lift during takeoff and landing. The trailing edge flaps and leading edge slats, when extended, increase the wing area and the effective wing camber, which greatly increases lift. Trailing edge flaps position 0 - 15 provide increased lift, position 15 - 40 provide increased lift and drag to permit slower approach and greater manoeuvring capability. [11]

d. Landing gear

The Landing gear is operated by hydraulic power. During gear retraction automatic braking is applied to the main gear wheels. Nose gear rotation is stopped by snubbers. When the nose wheel is retracted, it is enclosed by clamshell doors which are mechanically linked to the nose gear. [12]



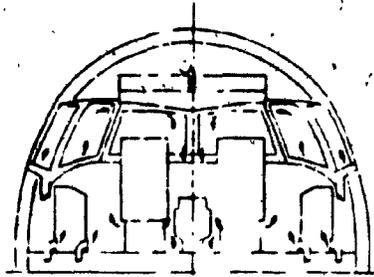
*FIGURE 1.4 High Lift Devices *

e. Air conditioning

Aircrafts operating at high altitudes are subject to a wide range of temperatures. At 35,000 feet the air temperature is approximately -67 degrees Fahrenheit. To provide a comfortable interior temperature, an aircraft must have a very effective air conditioning system.

The heart of the air conditioning is an electro-mechanical unit called pack. The pack system operates from a source of air from the pneumatic system and produces a supply of conditioned air that is controlled to maintain selected temperatures and ventilation rates within the aircraft zones. The packs are installed in the fuselage unpressurized area with control valves for controlling air flow. Preconditioned air is supplied by a combination of bleed air from the engines, gas turbine compressor or ground air compressors. Air conditioning is accomplished by a refrigeration unit which essentially consists of air to air heat exchangers, compressor/turbine and bypass valves. [10]

In this chapter, various aircraft parts that produce sounds were described. In the following chapter these sounds are examined more closely by means of acquisition and analysis.



FLIGHT DECK AIR-CONDITIONING

*FIGURE 1.5 Air Conditioning *

CHAPTER 2

2.1 INTRODUCTION

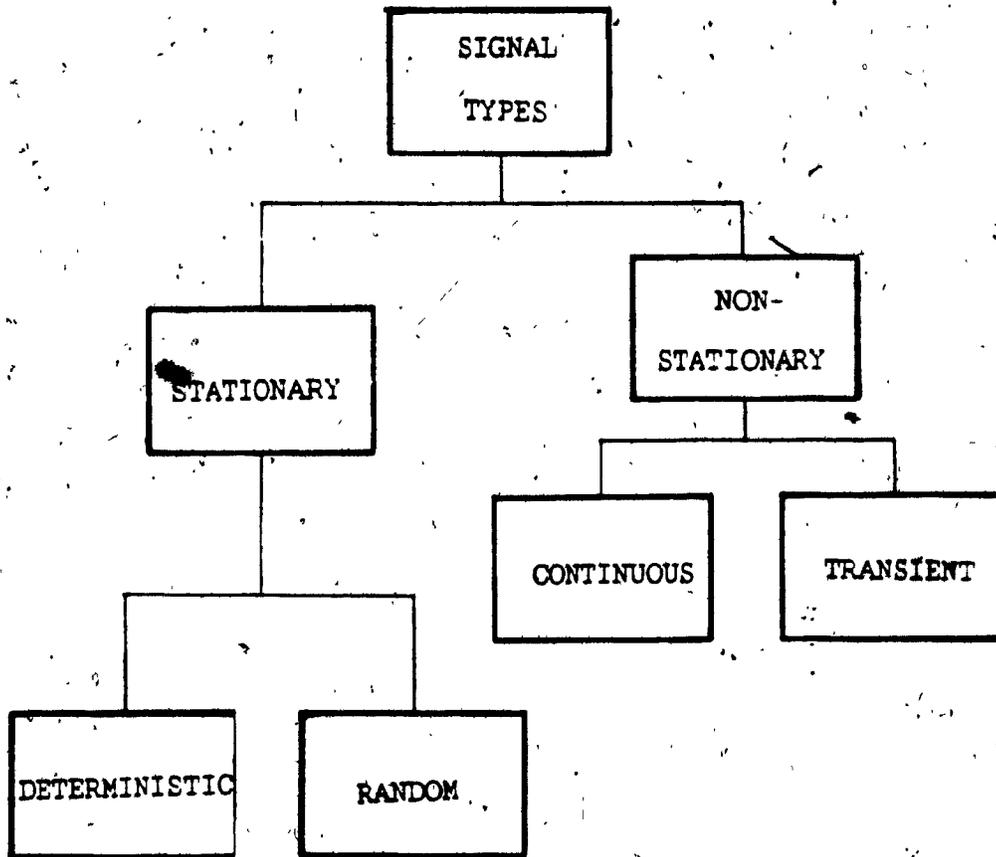
The sounds which are heard in the flight compartment are recorded and analyzed. To facilitate the analysis they are classified according to their time domain characteristics. Signal classification, sound data acquisition and analysis, is the purpose of the present chapter.

2.2 SIGNAL CLASSIFICATION

The sound signals that are present in the cockpit, are classified into the following dominant types : Stationary, and Non-Stationary.

2.2.1 Stationary

Within the framework of this project, stationary signals will be defined as those whose average properties do not vary with time (to a certain extent) and are thus independent of the particular sample record used to analyze them. [14]



*FIGURE 2.1 Signal Classification *

Almost all sounds audible inside the cockpit during a steady state flight configuration, belong to this type. The stationary signals can be further subdivided into :

- a. Deterministic, which are made up entirely of sinusoidal components at discrete frequencies.
- b. Random signals, having a spectrum which is continuously distributed with frequency.

An example of a deterministic signal is the engine whine, and of a random signal the aerodynamic hiss. Figure 2.2 presents this example.

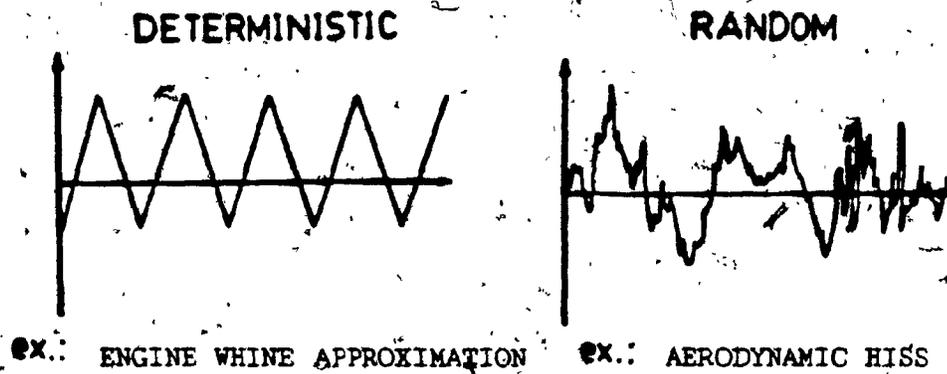
2.2.2 Non-stationary

Although the term "non-stationary covers all those signals which do not satisfy the requirements for stationary signals, the majority of useful non-stationary signals are such that they can be divided into short quasi-stationary sections. These signals are subdivided into Continuous and Transient types. [14]

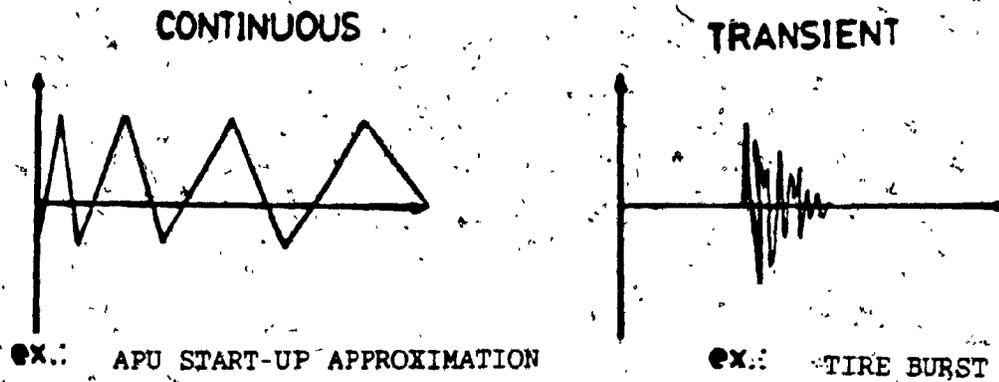
a. Continuous

All those non-stationary signals which consist of a summation, in time, of quasi-stationary sections.

example: windshield wipers, APU start up. See figure 2.3



*FIGURE 2.2 Example Of Stationary Signals *



*FIGURE 2.3 Example Of Non-Stationary Signals *

b. Transients

Transient signals are defined as those which have a very short duration, and fast amplitude rise and fall. Examples of these sounds are the various bang sounds, such as tire burst, gear up and down lock, etc.

1 SIMULATION PREPARATION

1.1 Introduction

The first two preparatory steps for a realistic sound simulation are: Data acquisition, and Data analysis.

Data acquisition is the process of obtaining recordings of sounds as heard inside the flight compartment. The recordings are then analyzed and data in the form of frequency spectrum components and amplitude variations for specific sounds, are obtained. These data are used by the sound system as reference for the simulation.

1.2 Data Acquisition

The sound data recordings are supplied by the aircraft manufacturer or the airline company. These recordings contain sounds which are considered appropriate for training purposes. One method of acquisition is shown in figure 2.4. The equipment which are used for this purpose are a microphone, a sound level meter and a portable cassette recorder.

Care is taken during this period to ensure that the recordings were as free as possible from all other sounds, such as talking, auxiliary sounds which could be turned off, and sounds from other aircraft or vehicles in the vicinity.

At the beginning of each recording, a calibration tone is fed into the sound level meter. This is to verify any drift in calibration or speed that could occur, following an extensive use of the cassette recorder. The location and orientation of the microphone is selected such as the recorded data represent the flight deck sounds.

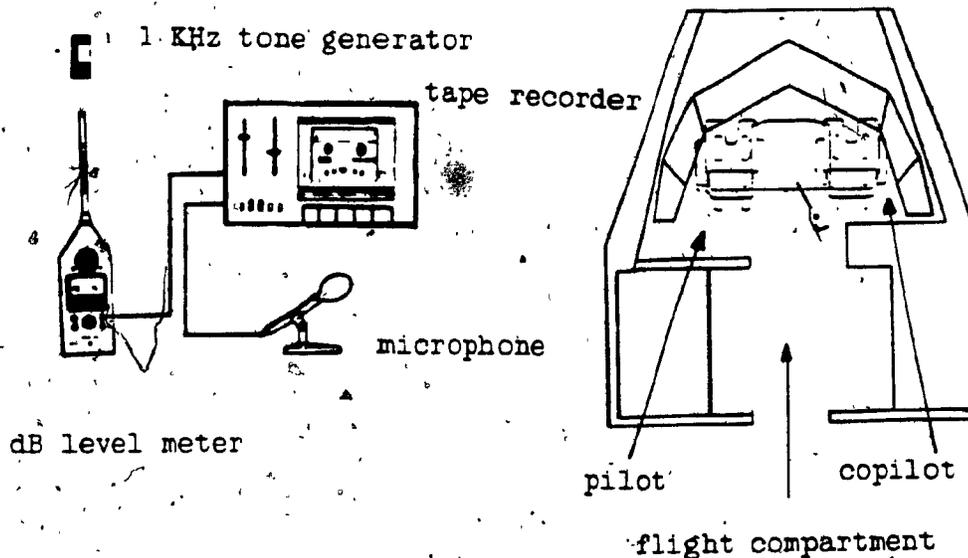


FIGURE 2.4 Data Acquisition

Test conditions cover a wide range of events which occur during normal ground and flight operations.

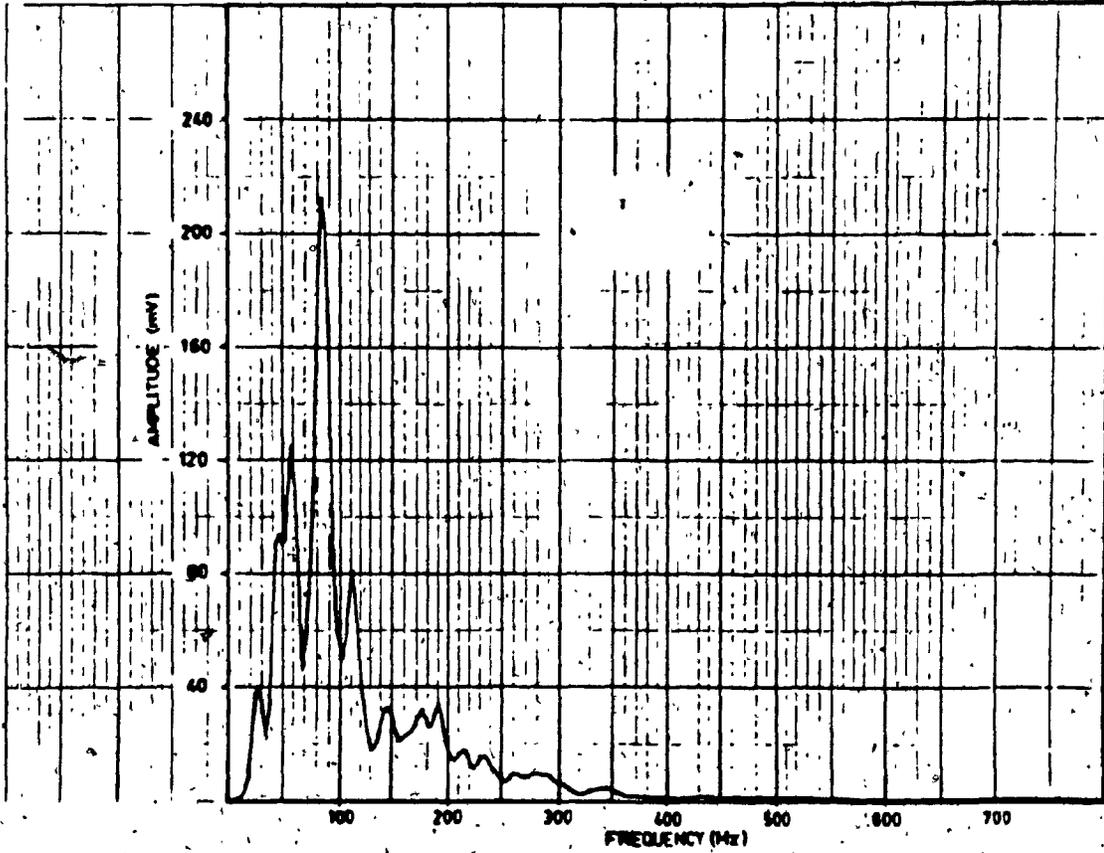
A typical tape begins with a calibration tone followed by a no-input period. The second section of the recording is used to analyze the importance of the tape background noise. The remaining part is made up of calibrated flight deck sounds on one channel and comments on the flight conditions on the other.

2.3.3 Analysis Procedure

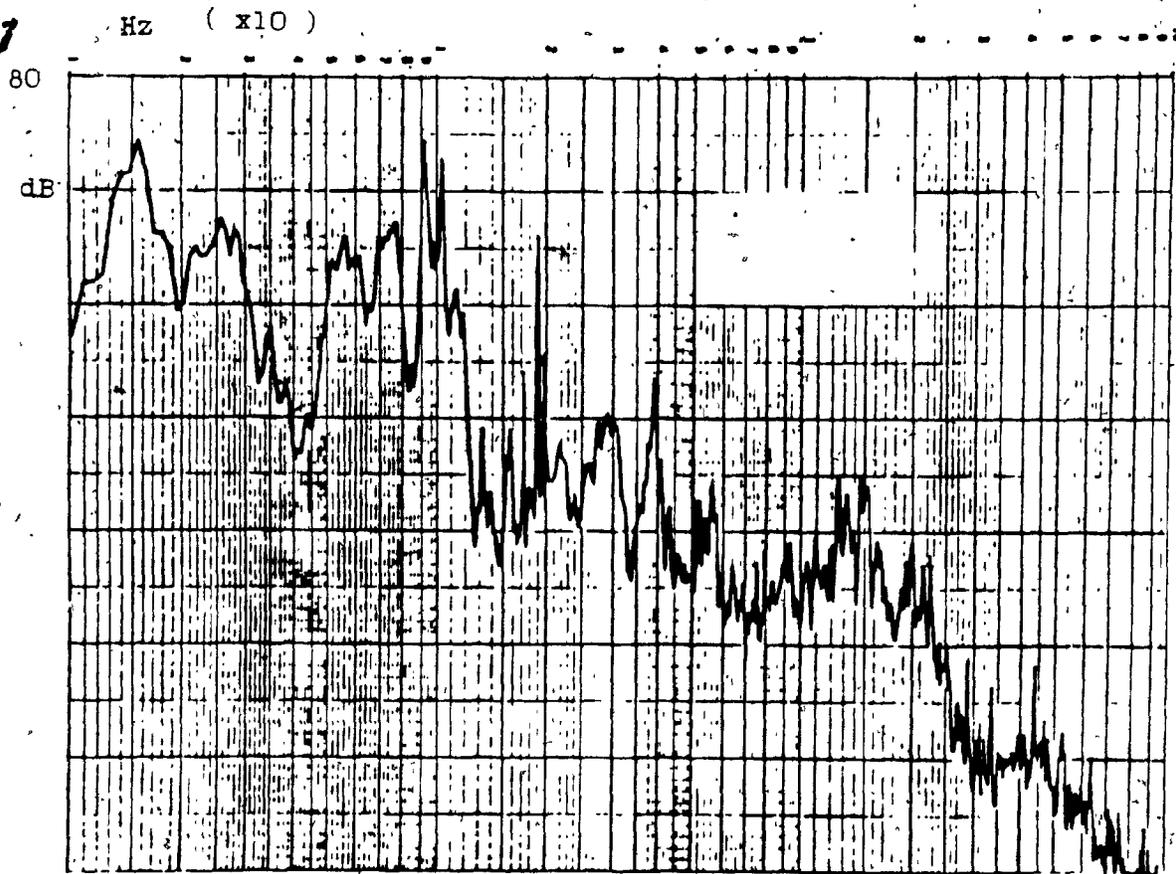
Each signal, depending on its type and frequency range, requires a special kind of analysis. [1],[13],[14]

a. Stationary signals

Provided that the signal to be analyzed lasts uninterrupted for a minimum of 10 seconds, a conclusive frequency analysis can be performed (FFT). Low frequency signals are analyzed using a linear scale, while high frequency whine and random noise use a logarithmic scale. (Refer to figures 2.5 and 2.6) The sound recording (tape) is played back using the tape recorder, the signal is processed by the spectrum analyzer and is recorded on a built-in cassette, and finally its frequency spectrum is produced on a plotter. [14]



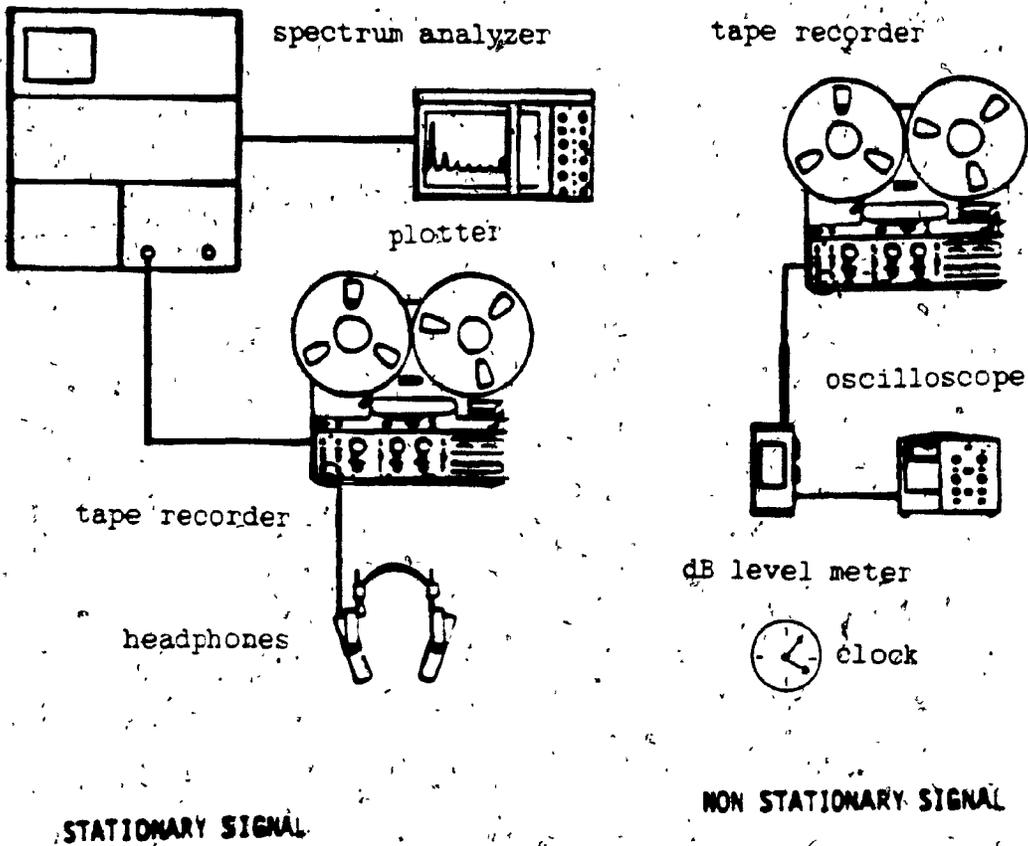
*FIGURE 2.5 - Engine sounds analysis on a Linear Scale *



*FIGURE 2.6 Engine sounds analysis on a Logarithmic Scale *

b. Non-stationary signals

When the signal varies too rapidly to permit a valid FFT analysis to be performed, alternate set ups are used. One method of analysis is represented in figure 2.7. This method is mainly used to measure the time that takes for a specific sound to reach its steady state condition. The sound is played back, and its amplitude variation in time is observed and measured with a dB level meter, an oscilloscope and a clock. [14]



*FIGURE 2.7 Analysis Setups *

For analysis purposes, the following equipment were used:

Spectrum Analyzer,

Plotter,

Stereo tape recorder

Sound level meter

Oscilloscope

Clock

Appendix B supplies the information on some of the instrumentation used.

2.3.4 Effect Of Background Noise

A very important factor in the analysis is the effect of the background noise level. Figure 2.8 shows the correction that has to be made on the total noise level measured. If the difference between the total and the background noise is greater than 10 dB, then this extra noise presents a negligible effect on the measurement of the signal source, and the data obtained are accurate and useful for the simulation. If the difference is less than 3 dB, then the correct level has to be regarded as an approximate measurement and it can not be used with confidence as reference for the simulation. The in-between values can give a reasonable estimate of the actual noise level. Whenever there is a doubt on the results of simulation, a period of fine tuning in the presence of training personnel follows.

If during the recording the Sound Level Meter is set properly, the signal to noise ratio of the data acquisition system will prevent $L(\text{signal} + \text{noise}) - L(\text{noise})$ from being less than 10 dB. See figures 2.9, 2.10, 2.11.

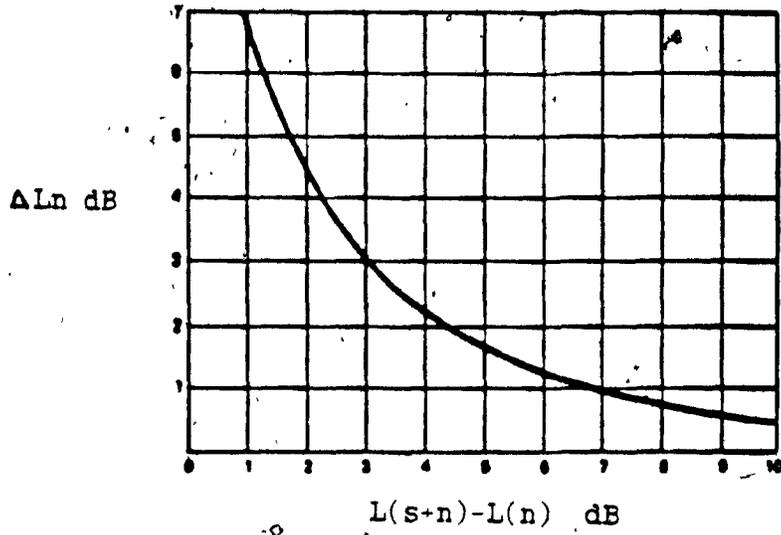
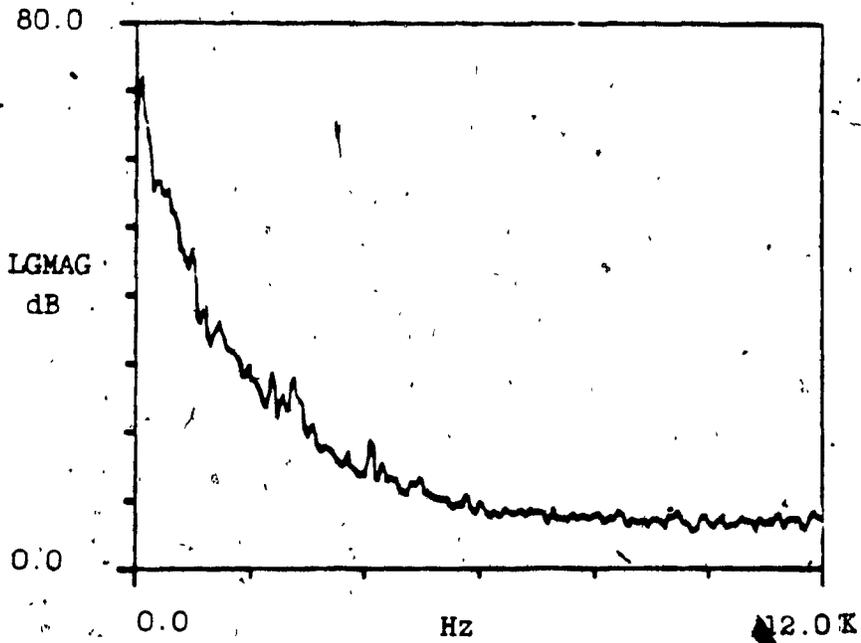
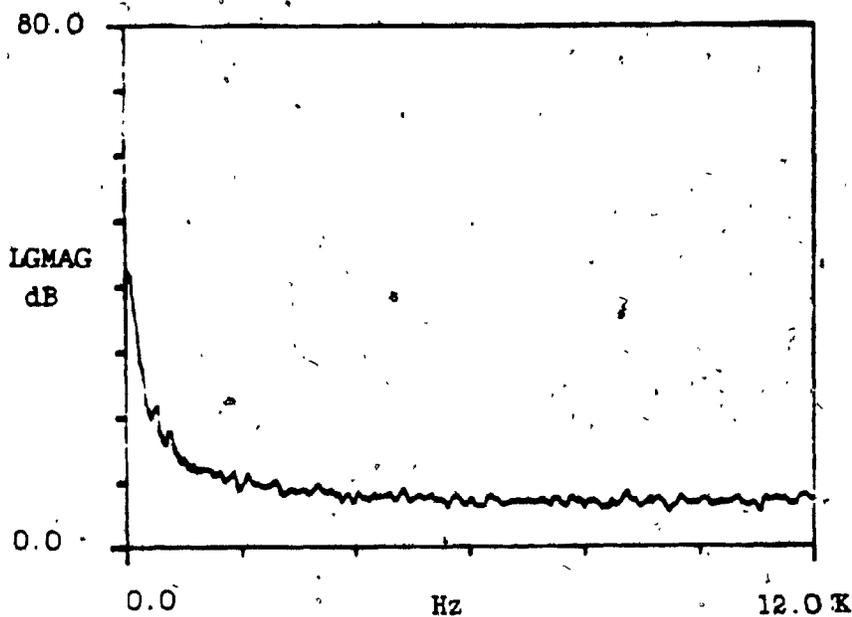


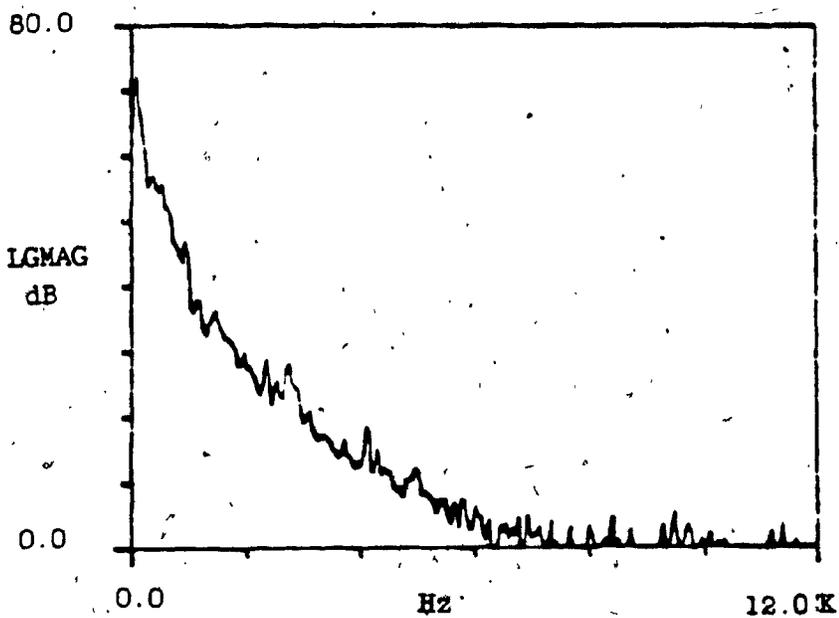
FIGURE 2.8 Noise Correction Curve.



*FIGURE 2.9 Takeoff Sound With Tape Noise *



*FIGURE 2.10 Tape Background Noise *



*FIGURE 2.11 Takeoff Sound Minus Tape Noise *

2.4 DISCUSSION

In this chapter the sound signals were classified, and a method of data acquisition and analysis were presented.

Since measurement and evaluation are quite subjective as far as human hearing is concerned, the results of spectral analysis are quite essential to evaluate differences between the simulator and the aircraft flight deck sound.

Noise recordings and reproduction inside a closed area such as a cockpit, are influenced by :

1. Sound reflection and absorption by the interior surfaces.
2. Reflections from and absorptions by objects within the cockpit, such as seats and people.
3. External noise sources and the transmission characteristics of the structure.
4. Air absorption (ambient temperature and humidity).

All these parameters create problems when similarity of test conditions are needed. To overcome these problems a tuning session is introduced, and as a result the simulated sounds compare favourably with the recorded ones in the aircraft. [5]

In the following chapter the sound system hardware and background subroutines are described.

CHAPTER 3

3.1 SYSTEM DESCRIPTION

The sound analysis is done first using the sound tapes and the flight conditions - data, which are provided by the aircraft manufacturer. These tapes contain sound data which are considered to be significant for training purposes. In the sound analysis each sound is being examined for its type and it is decomposed into its frequency and amplitude components:

Starting from this analysis then, all sounds are classified into the following categories:

- a. Repetitive (or continuous) type.
- b. Random.
- c. White noise.
- d. High frequency.

Examining the sounds produced by the various aircraft parts and systems, table 3.1 was assembled.

| SYSTEM | REPET. | RANDOM | WH. NOISE | HIGH FR. |
|---------------------|--------|--------|-----------|----------|
| ENGINE | X | X | X | X |
| ENGINE STALL BANG | X | X | | |
| SPOILER AERONOISE | | X | | |
| L/G AERONOISE | | X | | |
| AERODYNAMIC HISS | | | X | |
| RUNWAY RUMBLE | X | X | | |
| DUCT AIRFLOW | ✓ | X | X | |
| HYDRAULIC PUMPS | | | | X |
| CABIN DECOMPRESSION | X | | X | |
| WINDSHIELD WIPER | X | | | X |
| GROUND POWER UNITS | X | | | |
| RAIN AND HAIL | | X | X | |
| CRASH | | X | | |
| APU | | | | X |
| TIRE BURST | X | X | | |
| GEAR UP BANG | X | X | | |
| THUNDER | X | X | | |

Table 3.1 sound types

The sound generation is done using two different systems :

a. Sounds with main frequency components below 1 KHz are produced digitally using a microprocessor system and then converted to an analog signal using a 12-bit fast digital to analog converter. This way, stationary waveforms of complex spectral characteristics can be computed and stored in tables off-line. See figure 3.1. [4]

b. Due to the speed limitations of the microprocessor, components higher than 1 KHz are generated using voltage controlled oscillators, and white noise generators on standard PCB cards (fig. 3.2). [5]

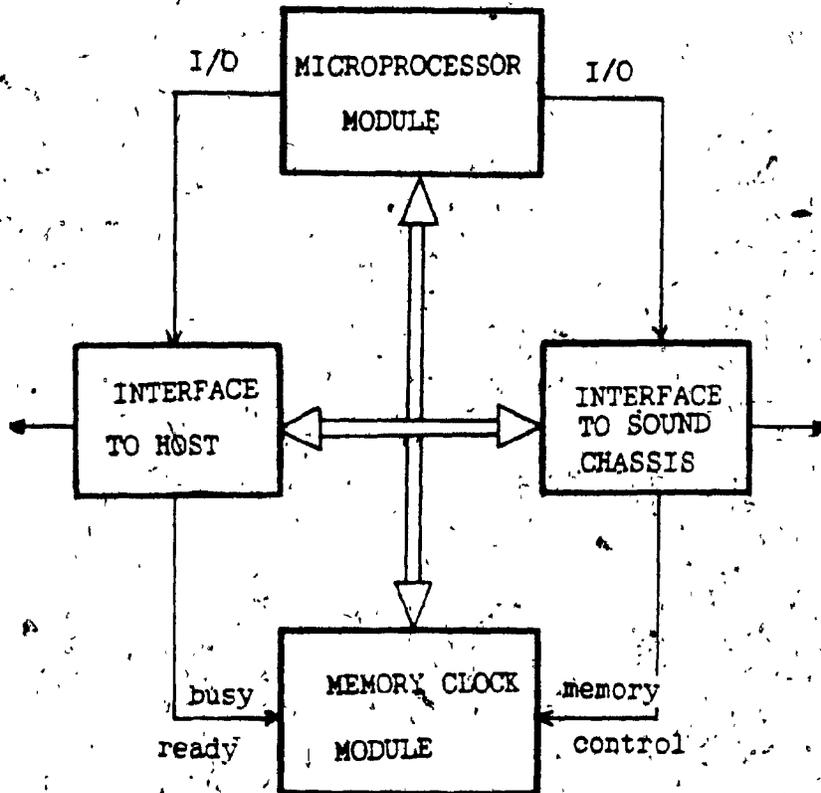
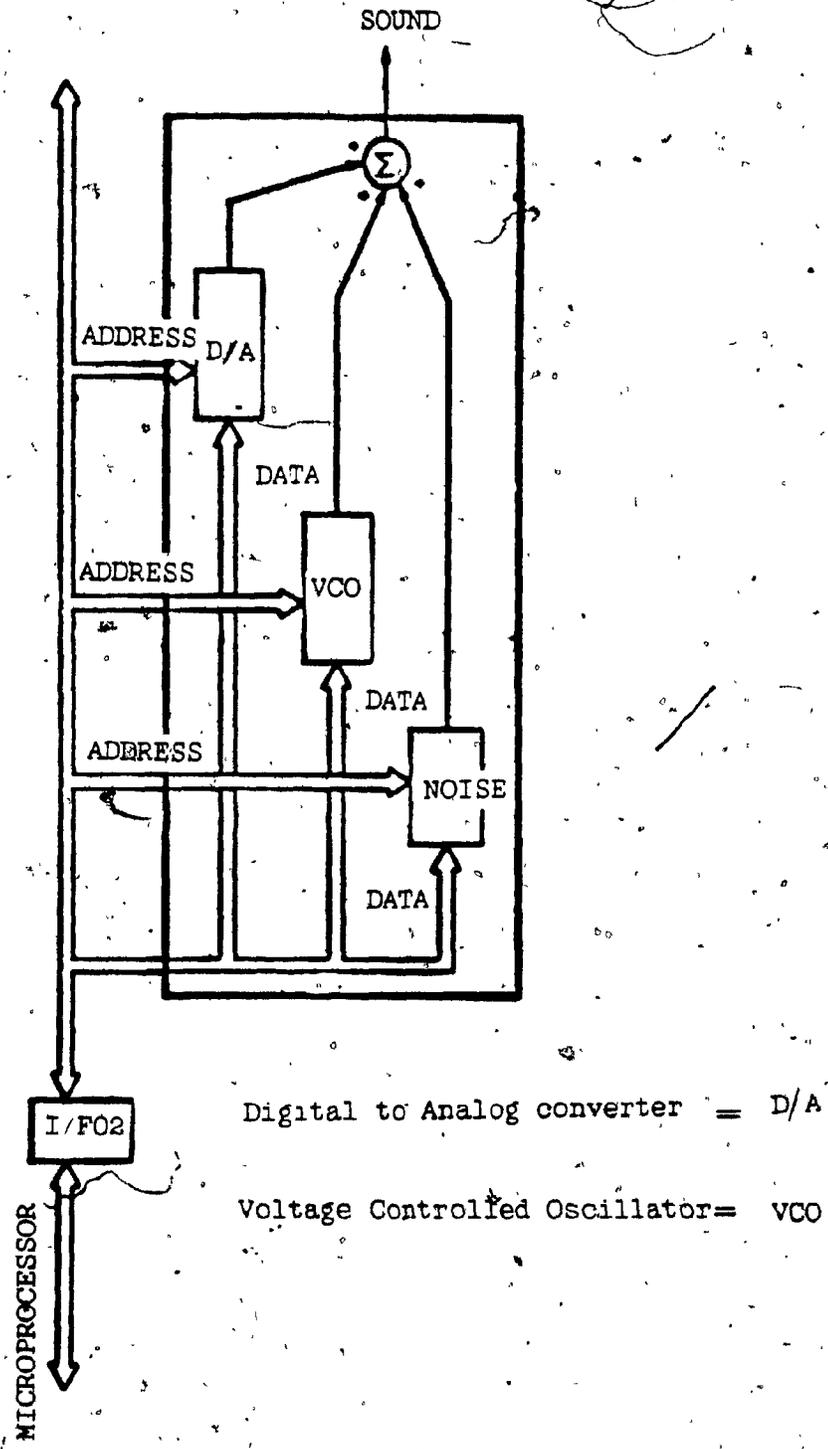


FIGURE 3.1 Microprocessor System



*FIGURE 3.2' Sound Generator Module *

Information from both systems is distributed to a six channel sound chassis. Seven speakers are installed inside the cockpit simulator - two of them in parallel - as shown in figure 3.3. The speakers are placed in such a way so that a multi-dimensional sound image is created around the pilot and copilot, and problems of sound directionality are solved. Table 3.2 describes the location of the loudspeakers, as well as some typical sounds reproduced by them.

| <u>CHANNEL</u> | <u>SPEAKER LOCATION</u> | <u>TYPICAL SOUND</u> |
|----------------|--|--|
| 1 | Left wall of flight compartment, behind instructor station | Left Engine, Tire burst, APU, GPU, Thunder, Flaps, Spoilers. |
| 2 | Right wall of flight compartment, opposite to instructor station | Right Engine, Tire burst, GPU, Thunder, Flaps, Spoilers. |
| 3 | Top left wall, behind pilots overhead panel | Aerohiss, Rain, Hail, Rapid decompression, Air-conditioning |
| 4 | Top right wall, behind copilots overhead panel | Aerohiss, Rain, Hail, Rapid decompression, Air-conditioning. |
| 5 | Under the simulator between pilot and copilot | Runway rumble, Touch down, Landing gear. |
| 6 | Nose area, under the windshield | Aerohiss, Rain, Hail, Wipers. |

*Table 3.2 Speaker location and Typical Sounds Description *

3.1.1 Generation Of Sounds Below 1 KHz

For this class of sounds, a system consisting of a microprocessor (AMD 2900, bit slice design), memory and interfacing is used. The microprocessor permits the generation of both repetitive and random sounds. The repetitive sounds are simulated by making use of word tables generated by the microprocessor and stored into its memory. Each table is associated with one particular waveform and consists of 2000 values describing the amplitudes of the individual frequency components of one cycle of the particular waveform. Any table can be modified, or deleted, or new tables can be added. See figure 3.6 which presents an example of table contents. By continuously stepping through a cyclic table at the sampling rate of 2 KHz and outputting values at fixed intervals through the table, a sound of a specific pitch is produced. Varying the step interval - equivalent to varying the frequency - the pitch of the sound can be changed. [4]

For a realistic simulation of aircraft sounds it is also necessary to be capable of generating random sounds of variable cutoff frequency and amplitude. A random number generation routine and a one pole digital filter are implemented in software and computed by the microprocessor. [4],[2] The equation used in this computation is the following :

$$J(i) = J(i-1) + (AMP \cdot I(i)) / 256 - (FREQ \cdot J(i-1)) / 256$$

where

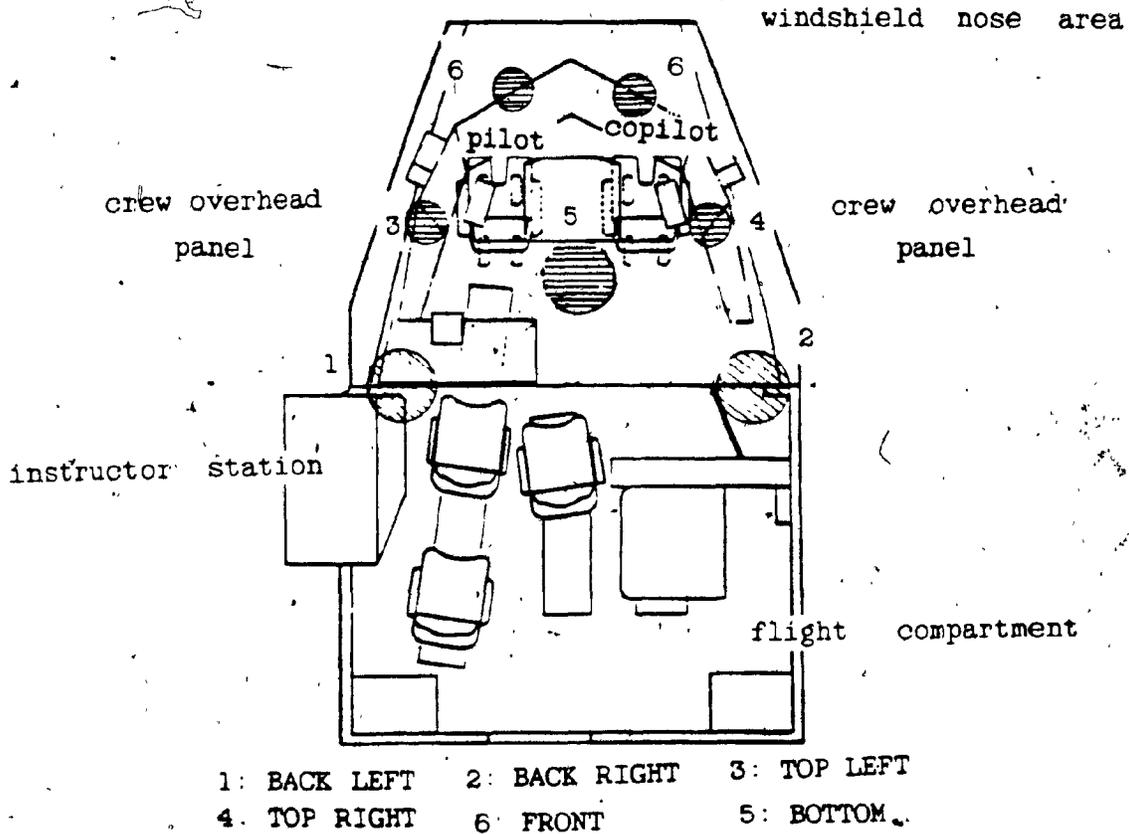
J = a 16 bit number which is updated and outputted at a rate of 2 KHz.

I = a 32 bit uniformly distributed number used in the random generation routine.

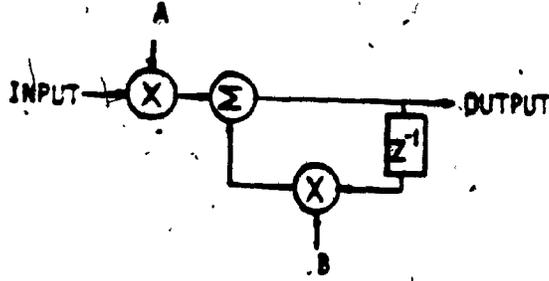
AMP = amplitude factor of the output sound.

FREQ = frequency factor of the ourput sound.

Refer to figure 3.4

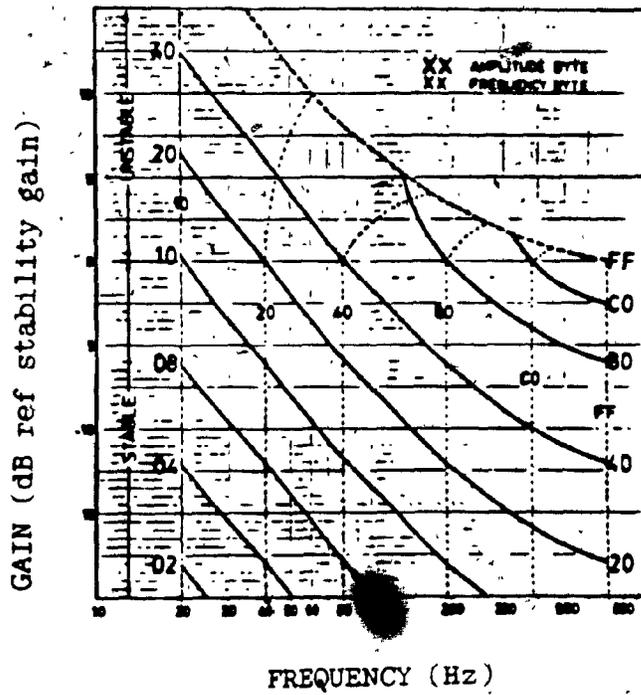


*FIGURE 3.3 Speaker Location



$A = AM/256$
 $B = 1 - FR/256$
 INPUT = I(1)
 OUTPUT = J(1)

FIGURE 3.4 Digital Filter



XX = byte

FIGURE 3.5 Digital Filter Response

For the implementation of the repetitive and random sounds two subroutines have been written and microcoded into the memory of the microprocessor system.

The first one, CNTW, handles all repetitive (continuous) sounds, and the second one, RNDS, handles all the random sounds. Each subroutine generates frequency and amplitude controlled signals and divide each signal's energy in a controlled manner between the seven loudspeakers installed in the simulator.

The input format of each of the subroutines is as follows:

a. CNTW : FREQ NADS ADRS AMP DIST

where

FREQ = a 16 bit integer ranging from 0 to 1000 given in Hz

NADS = adress in the microprocessor memory containing a counter N, ranging from 0 to 1999. The counter specifies the point in the 2000 word table that was outputted during the last

CNTW

ADRS = a 16 bit number specifying the top address of the particular wave table.

AMP = a 16 bit number whose low order byte specifies the amplitude of the wave.

DIST = a 16 bit number controlling the distribution of the signal among the loudspeakers, i.e.:

Front = 003 Bottom = 00C Top Left = 0C0
Top Right = 030 Back Left = C00 Back Right = 300

b. RNDS : FRAM IADS DIST where

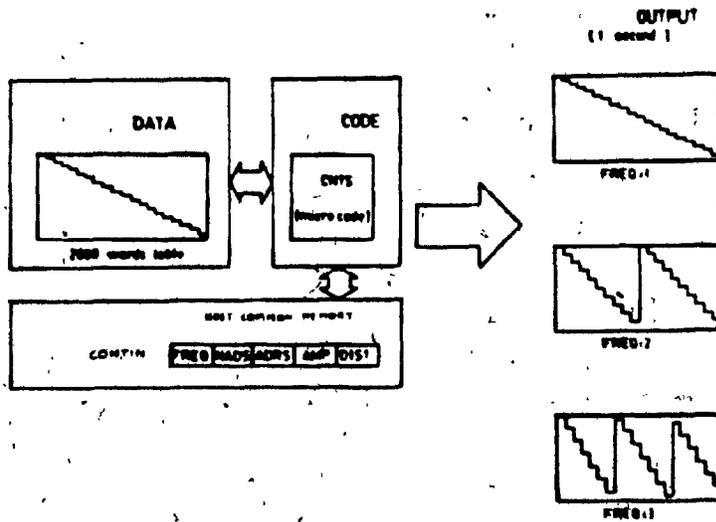
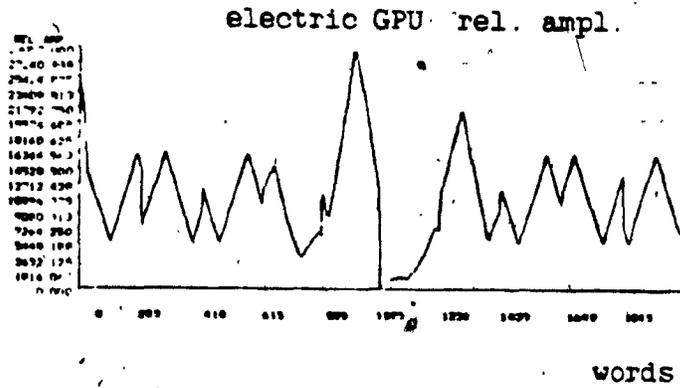
FRAM = a 16 bit number whose least significant byte specifies the amplitude, and the most significant one specifies the cutoff frequency of the filter discussed earlier.

IADS = a 16 bit number specifying the address in the microprocessor memory where the most significant byte of the previous number is stored.

DIST = a 16 bit number specifying the distribution among the speakers.

0.1 Generation Of Sounds Above 1 KHz

Sounds with frequency components greater than 1KHz are generated using voltage controlled oscillators and white noise generators, designed as mentioned on standard PCB cards. Each board consists of two VCO's with frequency and amplitude control, one white noise generator, dedicated in modulating the VCO waveforms, and two white noise generators, with amplitude and four step frequency controls. There is also a final volume control per channel. [5]



*FIGURE 3.6 Example of Table Contents *

3.2. SOUND SIMULATION SYSTEM OVERVIEW

3.2.1 Introduction

Having introduced the main components of the sound generation, we now proceed in describing the sound system incorporating these components. The system consists of the following components:

- a. Host computer
- b. Host to micro interface: I/F01.
- c. Microprocessor
- d. Microprocessor to sound chassis interface I/F02.
- e. Sound chassis
- f. Dual power amplifier modules - 6 individual amps -
- g. Seven loudspeakers.

a. Host computer

This is the main simulation computer. It does the actual simulation of all the systems by executing its Fortran programs. All operator actions are processed by the Host, which issues the appropriate responses to the various simulator systems.

b. Host to micro interface: I/F01.

It provides a means of communication between the host and the microprocessor.

c. Microprocessor

This system incorporates all the control, computation, processing and decision making capabilities. It is designed using the popular 2900 series of bit slices. Its functions are to control the various data transfers from the host computer to the sound chassis interface, run various diagnostic tests, compute, store, and output the sound data tables. Refer to figure 3.1 .

d. Microprocessor to sound chassis interface I F02.

Its main function is to carry information from the microprocessor to the sound chassis, and it also contains circuitry to check the status of the chassis power supplies.

e. Sound chassis

It contains the appropriate hardware for sound generation : 6 generator modules each of which consists of an address decoder, one 12-bit register, nine 10 bit registers, one D/A converter, two sinewave oscillators, and a noise generator. This noise generator can be used to modulate the sinewave oscillators. In addition, two noise sources, amplitude controlled, are summed up into one output with the above signals. Refer to figure 3.2

f. Dual power amplifier modules

These are the output signal amplifiers, one per output channel.

Y

each with 15 to 20 watts power output capability.

g. Seven loudspeakers.

These are located within the simulated cockpit area in such a way, as to provide sonic directionality.

The total system requirements then are best explained with the aid of figure 3.7 . .

The sound module monitors any change of status in the aircraft simulator, such as engines are ignited, APU is switched ON, is coded in Fortran and it is running in the Host. This module calculates the frequency and amplitude parameters of a desired output. During execution it generates the parameters for a group of sounds every 133ms through I F01. The calculation results are routed to the microprocessor. The microprocessor executes the sound routines to provide sound enabling as well as amplitude and frequency control data signals generating a train of digital data. Interface I F02 channels these data to the sound generating modules in the sound chassis. The sound output is generated by suitably controlling and mixing various signals from voltage controlled oscillators, noise generator, signals, and sound tables. The final signal is power amplified and it is reproduced on the loudspeakers.

When, for example, an oscillator circuit is addressed, the frequency parameter from the microprocessor drives the voltage controlled oscillator via the module I/F02. Similarly when an amplifier is addressed, the amplitude parameters via I/F02 drive the voltage controlled amplifier to regulate the intensity of the oscillator output signal. The output is combined with the noise generator output signal, and fed to the power amplifier module which drives the loudspeakers. Online control is performed by a CRT. [3]

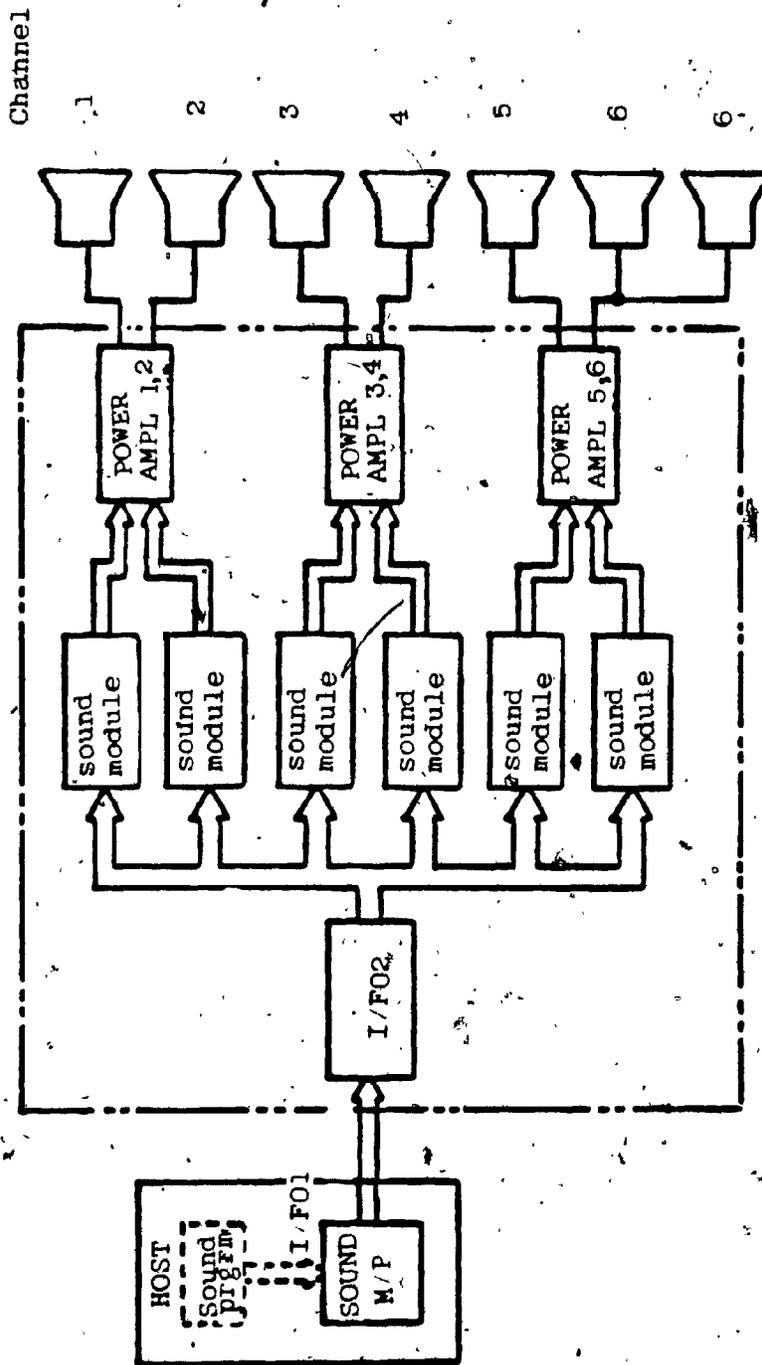


FIGURE 3.7 Complete System Description

CHAPTER 4

4.1 INTRODUCTION

Having examined the hardware and the various background software for sound generation, in this chapter, the parameters which are computed in the sound module to control the sound, are introduced. A general flow of the sound simulation is also presented.

4.2 PROGRAM REQUIREMENTS

In order to satisfy the microprocessor requirements the sound program must supply all the parameters, that is the computation results of frequencies and amplitudes for each of the desired sounds. These parameters are stored in a common memory block in the Host computer. The microprocessor picks up this information every 50 milliseconds, and sets up the various sound controls accordingly.

For the digitally generated sounds, ie. the ones whose main frequency component is below 1KHz, the microprocessor selects the proper table, and assigns the computed frequency.

amplitude, and distribution. It then outputs the table, sample by sample, to the Digital to Analog converter of the assigned channel the sound chassis. The same process is applied for the digitally generated random waveform.

For the sounds whose main frequency component is higher than 1 KHz and are generated by dedicated hardware, the frequency and amplitude parameters are control words, called word outputs.

A close examination of the sounds to be simulated, reveals that for a 4-engine aircraft, 12 repetitive, 12-random, 12-vco's, and 12-noise source waveforms fulfill the requirements. This can be easily verified by examining Table 3.1 in the previous chapter.

a. For the continuous sounds the following parameters are passed :

CONTINO1... to ...CONTIN12 where each parameter contains the five elements as described in pages 33 and 34 in the CNTW subroutine, that is :

- CONTINO1 (1) frequency
- (2) N-address
- (3) table address
- (4) amplitude
- (5) distribution

where I varies from 1 to 12.

b. For the random sounds the following parameters are passed

RANDOM01 to RANDOM12

where each label specifies the three elements requested by the RNDS subroutine.

RANDOM0I (1) cutoff frequency amplitude
 (2) I-address
 (3) distribution

where I varies from 1 to 12

c. For the non-digitally generated waveforms the following word output parameters are dumped by the microprocessor to the sound chassis to control the dedicated sound hardware :

1 volume control
 2 white noise generator amplitude control
 2 oscillator frequency controls
 2 oscillator amplitude controls
 2 random modulation controls

The sound chassis contains 6 sound boards each requiring 9 word outputs for control. A total then of 54 word outputs are assigned to 5 different labels. Refer to figure 4.1

VOLUME (1) to (6) volume of channel 1 to 6
 VCOA (1) to (12) oscillator amplitude
 VCOF (1) to (12) oscillator frequency
 VCOM (1) to (12) random modulation control
 NOISE (1) to (12) white noise control

Channel assignment is defined as follows

| | |
|-----------|--------------------------------|
| Channel 1 | Left speaker |
| Channel 2 | right speaker |
| Channel 3 | top left speaker |
| Channel 4 | top right speaker |
| Channel 5 | bottom speaker |
| Channel 6 | two front speakers in parallel |

The white noise generator word outputs NOISE, and the random modulation word outputs VCOM are assigned differently, so that the white noise cutoff frequencies can be changed. Although the final word outputs are the same, that is NOISE (1, 12), internal labels are used to sum up the effect as follows.

Formats

| | |
|------------------------|-------------------------------------|
| White noise generators | 1,3,5,7,9,11 |
| Data bits | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 |
| | X ---amplitude--- F1 B X X X X |
| White noise generators | 2,4,6,8,10,12 |
| Data bits | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 |
| | X ---amplitude--- F2 X X X X X |

where

F1 = frequency control

TRUE = 800 Hz. FALSE = 3600 Hz

F2 = frequency control

TRUE = 400 Hz. FALSE = 1600 Hz

B = Bursts :

.TRUE. = bursts .FALSE. = continuous, used
to modify the sound for the Rain and Hail effect.

X = not used

To control the burst rate when bursts are used on
generators NOISE(1,3,5,7,9,11), the word output
VCOM(2,4,6,8,10,12) can be used.

B is controlled by setting WNBURST 2,4,6,8,10,12, true or
false.

F1 is controlled by setting WNFSEL 1,3,5,7,9,11, true or
false, and

F2 is controlled by setting WNFSEL 2,4,6,8,10,12 true or
false.

The output is then computed as follows :

$$\text{NOISE}(\ast) = \text{WNOUT}(\ast) = \text{WNAMP}(\ast) + \text{WNFSEL}(\ast) + \text{WNBURST}(\text{even})$$

4 3 LIST OF CONTROL VARIABLES

The outputs to sound chassis are classified in the following
manner

| | SYSTEM | CHANNEL |
|--------|-----------------------|---------|
| VCOA01 | APU | 1 |
| VCOA02 | engine high frequency | 1 |

| | | |
|--------|-----------------------|---|
| VCOA03 | engine high frequency | 2 |
| VCOA04 | pneumatics | 2 |
| VCOA05 | spare | 3 |
| VCOA06 | spare | 3 |
| VCOA07 | hydraulics | 4 |
| VCOA08 | spare | 4 |
| VCOA09 | spare | 5 |
| VCOA10 | spare | 5 |
| VCOA11 | windshield wipers | 6 |
| VCOA12 | windshield wipers | 6 |
| VCOF01 | APU | 1 |
| VCOF02 | engine high frequency | 1 |
| VCOF03 | engine high frequency | 2 |
| VCOF04 | pneumatics | 2 |
| VCOF05 | spare | 3 |
| VCOF06 | spare | 3 |
| VCOF07 | hydraulics | 4 |
| VCOF08 | spare | 4 |
| VCOF09 | spare | 5 |
| VCOF10 | spare | 5 |
| VCOF11 | windshield wipers | 6 |
| VCOF12 | windshield wipers | 6 |
| VCOM01 | spare | 1 |
| VCOM02 | spare | 1 |
| VCOM03 | spare | 2 |

| | | |
|---------|----------------------------|---|
| VCOM04 | spare | 2 |
| VCOM05 | spare | 3 |
| VCOM06 | spare | 3 |
| VCOM07 | spare | 4 |
| VCOM08 | spare | 4 |
| VCOM09 | spare | 5 |
| VCOM10 | spare | 5 |
| VCOM11 | spare | 6 |
| VCOM12 | spare | 6 |
| NOISE01 | spare | 1 |
| NOISE02 | engine white noise | 1 |
| NOISE03 | engine white noise | 2 |
| NOISE04 | spare | 2 |
| NOISE05 | aerohiss | 3 |
| NOISE06 | rapid decomp rain and hail | 3 |
| NOISE07 | aerohiss rain and hail | 4 |
| NOISE08 | air conditioning | 4 |
| NOISE09 | spare | 5 |
| NOISE10 | spare | 5 |
| NOISE11 | spare | 6 |
| NOISE12 | spare | 6 |

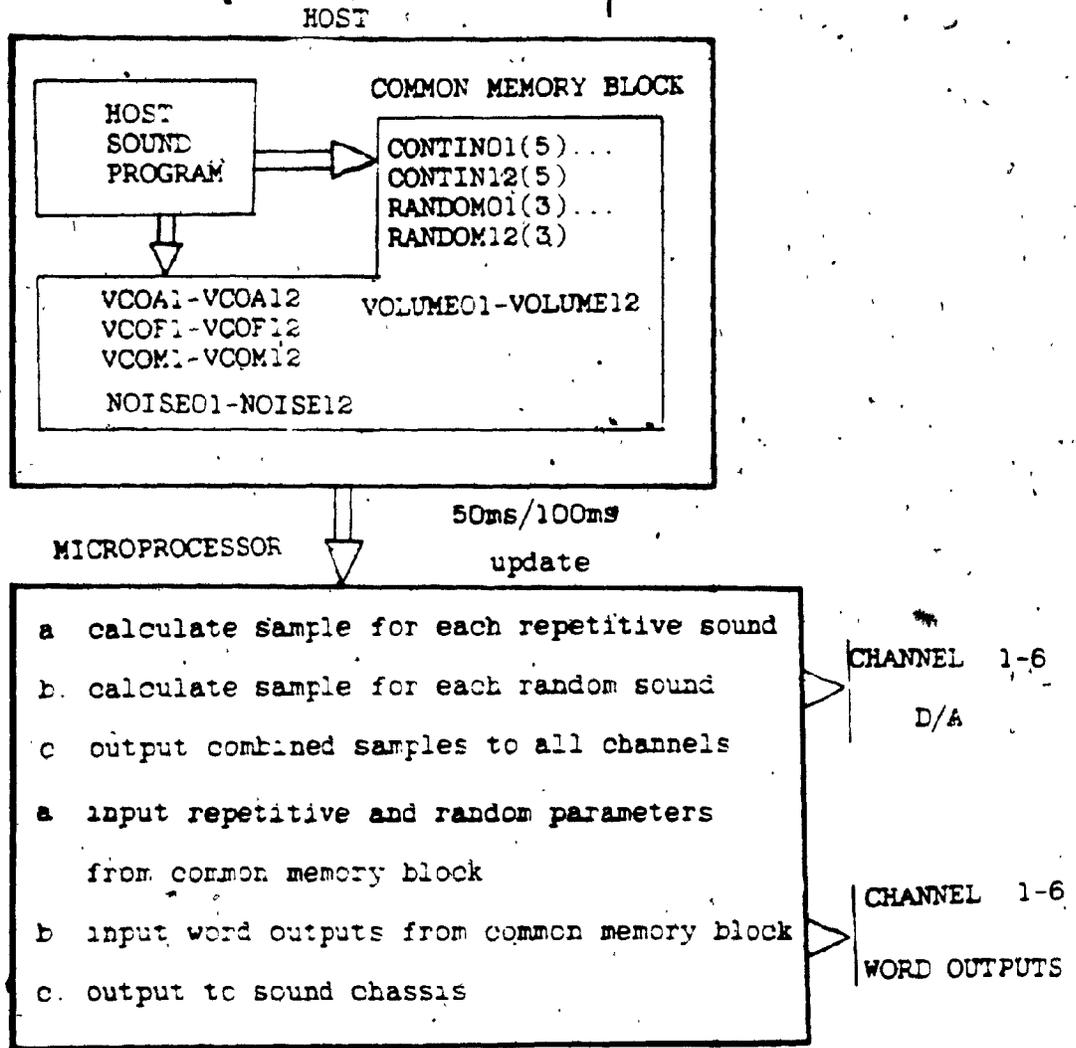
VOLUME 1 to 6 volume control

The channel assignments of the sounds controlled by the following parameters is not fixed, but variable.

RANDOM01 engine thrust noise
RANDOM02 engine thrust noise
RANDOM03 runway rumble
RANDOM04 spoilers noise
RANDOM05 air conditioning / rain hail
RANDOM06 landing gear aero noise
RANDOM07 rain and hail
RANDOM08 flaps noise
RANDOM09 bang sounds
RANDOM10 crash
RANDOM11 crash
RANDOM12 spare

CONTIN01 engine output table
CONTIN02 engine output table
CONTIN03 runway rumble
CONTIN04 electric ground power unit
CONTIN05 pneumatics
CONTIN06 windshield wipers
CONTIN07 runway rumble
CONTIN08 bang sounds
CONTIN09 spare
CONTIN10 spare
CONTIN11 thunder
CONTIN12 spare

In this chapter the various sound parameters, which are used in the sound program computations, were defined. The following chapter presents this simulation program.



*FIGURE 4.1 System Software Conception

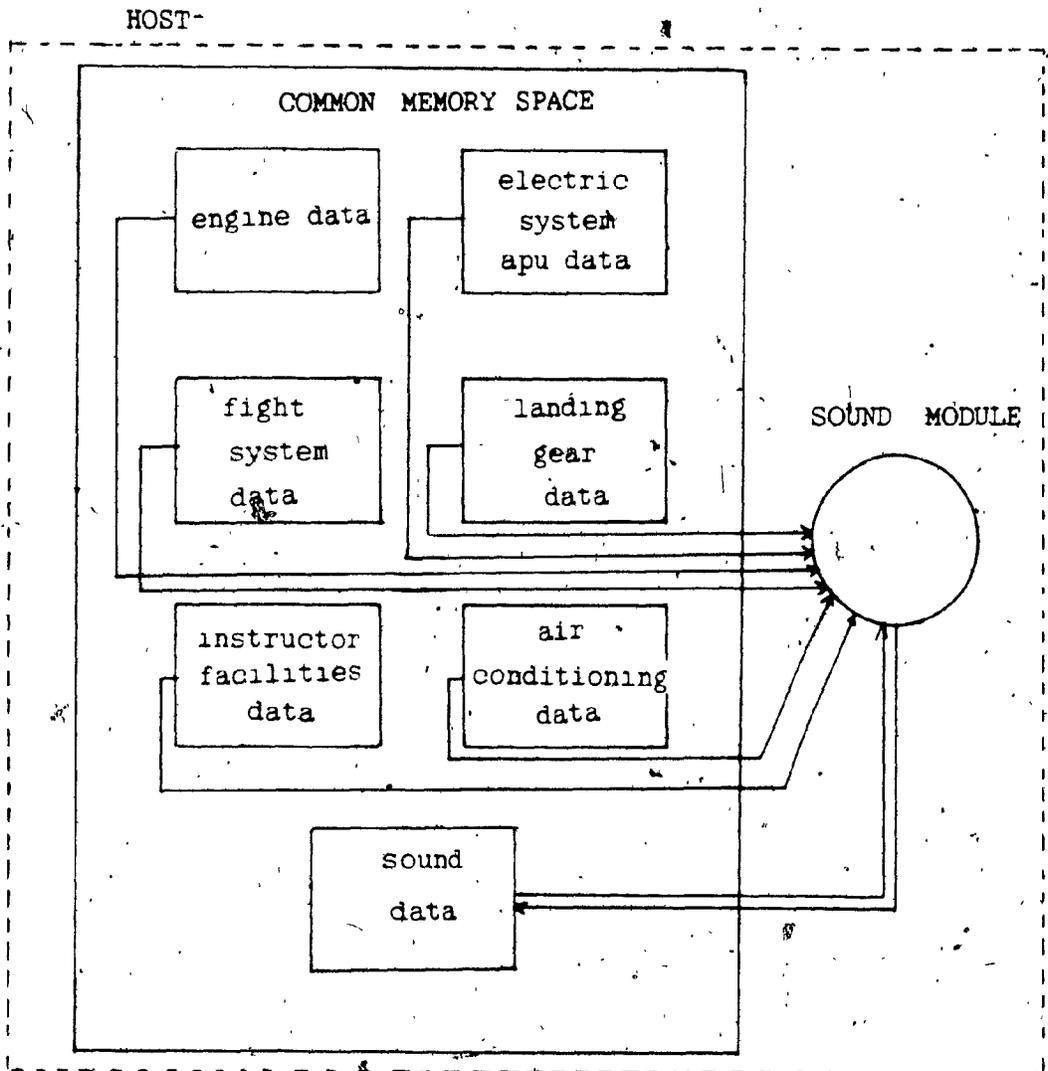
CHAPTER 5

5.1 INTRODUCTION

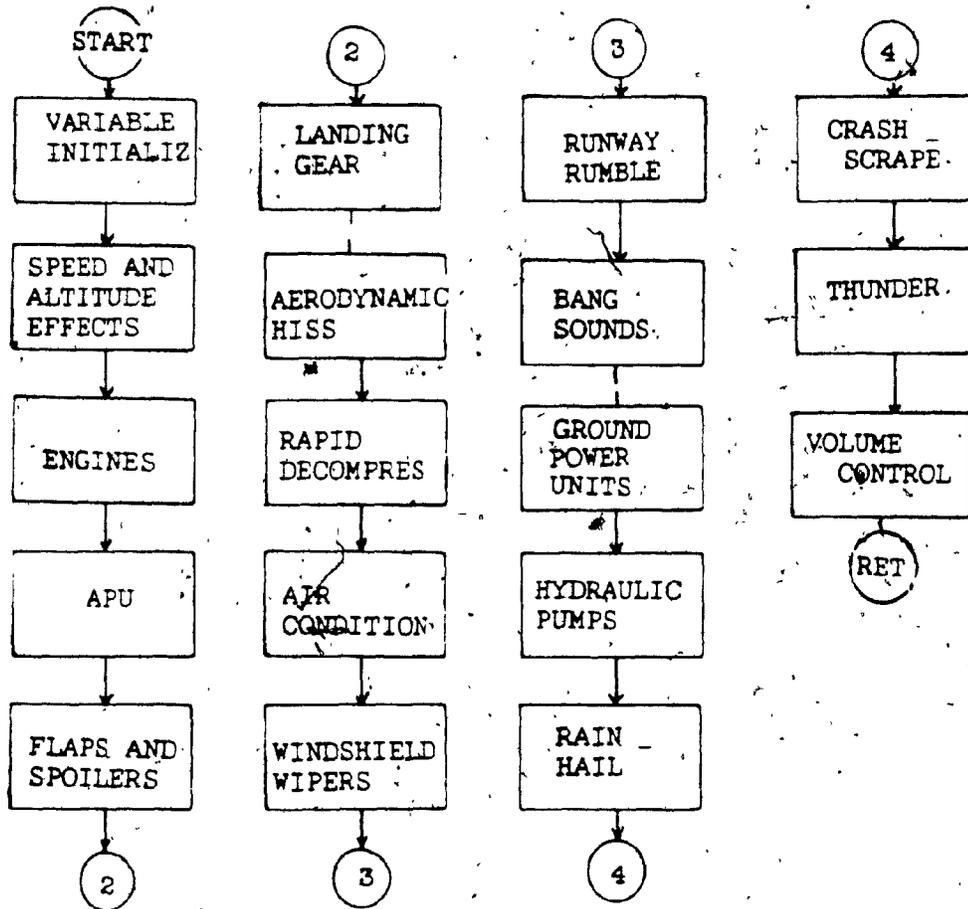
Simulation is achieved by breaking up the whole simulation task into smaller modules, and each module is responsible for simulating a specific system, for example engines, flight, sound, etc. These modules are coded as subroutines with assigned priority, and they are called by the main simulation program and executed according to their priority. The results of the computations of these modules are stored in a common shareable memory space in the Host.

The sound subroutine is called every 133 milliseconds. It reads from the common memory space the parameters computed by the other modules, and it uses them for its own calculations of frequency, amplitude and sound distribution parameters. These parameters are then stored in the common memory space. The microprocessor uses this information to set up the sound chassis control parameters.

The most common systems which supply information to the sound module are : The Flight systems which provide data on speed, altitude, speed brakes, direction, flaps spoilers etc. The Electric systems which provide data on braker status, the Landing gear system giving information about the position of the landing gear, and tires; the power plant supplying data concerning the engines, fuel flow, the turbine fan revolutions, thrust, etc. And last, the instructor facilities for various simulation controls and malfunctions. This is shown with the aid of figure 5.1. A high level block flowchart presents the flow of the sound program.



*FIGURE 5.1 Sound Subroutine Communication *



*FIGURE 5.2 Sound Module Block Flowchart *

5.2 ENGINE SOUNDS

This section describes the Engine system, and computes all the parameters required for the generation of engine sound.

5.2.1 System Description

The engine sound is dependent upon the fuel flow and the revolutions per minute of the engine fans. As the throttles are advanced from the idle position to maximum, information on the engine RPM (revolutions per minute of the N1 and N2 rotors) and FF (fuel flow), are provided.

Based on the analysis the following components are used to simulate the engine sound : [7] Refer to fig. 5.6, 5.7, 5.8 .

- a. A random noise of varying amplitude with a low cut off frequency, varying slightly as fuel flow reaches its maximum.
- b. A low frequency component (pure tone) with changing amplitude, and frequency varying from 125 Hz at idle, to 800 Hz at maximum RPM of the N2 rotor.
- c. A high frequency component of changing amplitude, and frequency varying from 750 Hz at idle to 3.0 kHz at maximum RPM of the N1 rotor.
- d. A random waveform of white noise quality representing the in-take aerodynamic hiss.

Examining the graphs supplied by the aircraft manufacturer, one has to be careful not to consider the various sounds produced by the flight instruments. They are identified easily because they are 400 Hz harmonics, present in almost all conditions. [7] Refer to engine shapers in Appendix C

The sound can then be generated as shown in the block diagram of figure 5.3

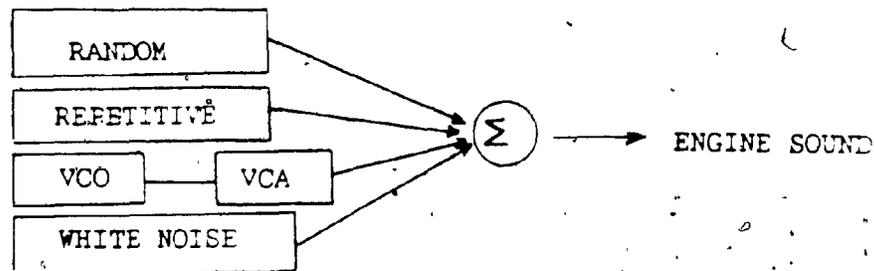


Figure 5.3 Engine Sound Block Diagram

5.2.2 Program Description

Aircraft sounds as heard inside the flight compartment are dependent on forward speed and altitude. The variable AMPLFN takes into account this effect and is used to adjust the noise levels of the sound components. The computation is done as follows (see Appendix C for a sample derivation):

$$RSP1 = (ALTITU - VHH) * OLTITU$$

$$RSP2 = (SPEED - VVE) * SPODE$$

$$AMPLFN = MAX(MIN(RSP1, RSP2), 0.0) \quad \text{equation 1}$$

where

| | |
|---------------|--|
| RSP1 | temporary variable |
| RSP2 | temporary variable |
| ALTITU | altitude constant |
| SPEED | speed constant |
| VHH | equivalent pressure altitude variable (feet) |
| VVE | equivalent airspeed variable (knots) |
| OLTITU. SPODE | tuning constants |
| AMPLFN | total amplification factor variable |

Each sound component then is computed as follows

a Thrust noise (random noise)

The amplitude is calculated in the following manner

$$\begin{aligned} \text{SNDWFS}(I) &= ((\text{EWF}(I) \cdot \text{FORTHR} \cdot \text{AMPLFN} - \text{SNDWFS}(I)) \\ &125 - \text{SNDWFS}(I) \cdot \text{AMPLFN} \cdot \text{EWF}(I) \cdot \text{REVTHR} \\ &\cdot \text{EDREV}(I)) \end{aligned} \quad \text{equation 2}$$

where

| | |
|--------|---|
| I | the engine number (1=left, 2=right engine) |
| SNDWFS | amplitude factor for thrust level |
| EWF | equivalent fuel flow variable (pounds/hour) |
| FORTHR | forward thrust level constant |
| REVTHR | reverse thrust level constant |
| EDREV | equivalent reverse door position varying from 0 (closed) to 1 (open) |

The sound amplitude is then outputted as follows

$$\begin{aligned}
&= 12 && \text{if } 255 < \text{SNDWFS}(I) \\
\text{RANDOMC1}(1, I) &= \text{SNDWFS}(I) - 256 && \text{if } 127 < \text{SNDWFS}(I) \leq 255 \\
&= \text{SNDWFS}(I) && \text{otherwise}
\end{aligned}$$

equation 3

The relation between the frequency of the thrust noise and the engine parameters (fuel flow, N1 and N2 RPM) is found to be approximately linear

The frequency is computed as follows

$$\text{RANDOMC1}(2, I) = \text{MIN}(\text{THRUST}, \text{EWF}(I) - \text{INITHRFR}) \cdot 127 \cdot 0$$

equation 4

where

- THRUST tuning frequency constant
- INITHRFR tuning frequency constant
- EWF equivalent fuel flow variable (pounds hour)

b High frequency component (N1 rotor revolution)

This sound is produced by the rotation of the fan blades

The amplitude of the high frequency component is approximated with a piece-wise linear function of the N1 RPM value

$$\text{VCOA}(I) + 1 = \text{AM2}(I) \cdot \text{HIAMP} \quad \text{equation 5}$$

where

I the engine number
 HIAMP is a tuning constant
 AM2 is the function as described in fig. 5 5

The frequency of the high frequency component is calculated through the empirical formula

$$VCOF(I - 1) = (A \cdot INN1P(I) - B) \cdot AMPHI \quad \text{equation 6}$$

where

I the engine number
 AMPHI pitch correction constant
 INN1P equivalent N1 RPM variable
 A, B are constants

c Low frequency component (N2 rotor revolution)

Analysis in the lower portion of the frequency spectrum showed an amount of some discrete frequency components present only at low N2 values. A linear function of the N2 RPM simulates the frequency content whereas the amplitude follows a piece wise linear model.

The amplitude is computed as follows

$$CONTINCI \cdot 4 \cdot I \cdot AM \cdot I \cdot LOWAMP \quad \text{equation 7}$$

where

AM is the function described in fig. 5.4

LOWAMP is a tuning constant

The frequency of this sound component is calculated as follows:

$$\text{CONTINCF}(I) = \text{LOWFRE} \cdot \text{INN2P}(I) + \text{OFFSET} \quad \text{equation 8}$$

where

I the engine number

LOWFRE tuning frequency constant

INN2P N2 rotor RPM

OFFSET tuning frequency constant

d White noise based on amplitude of thrust noise

$$\text{WNAMP}(I) = \text{SNDWFS}(I) \cdot \text{ENGWHITE} \quad \text{equation 9}$$

where

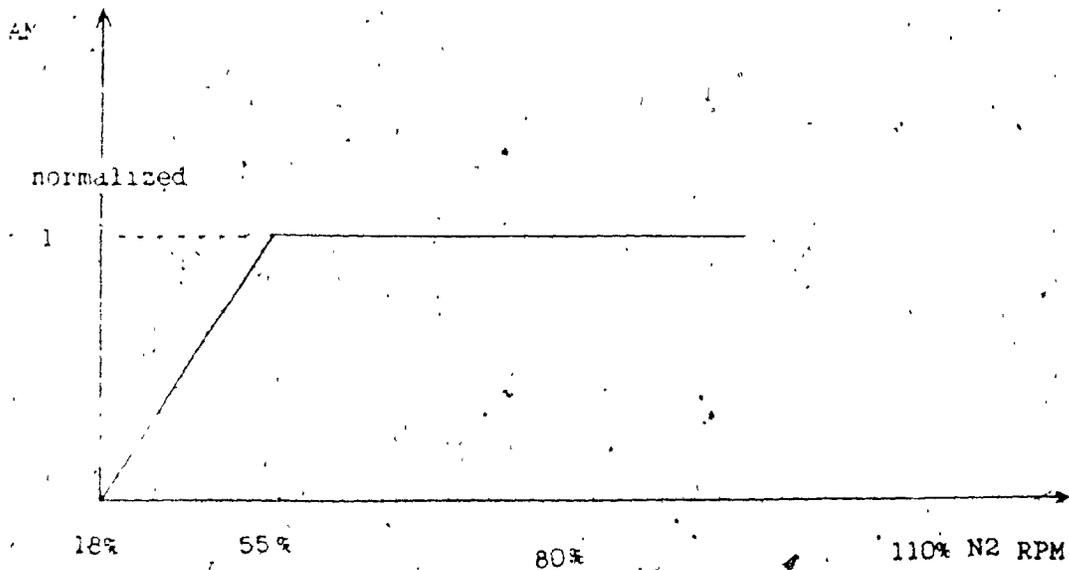
I the engine number

SNDWFS amplitude factor for thrust level

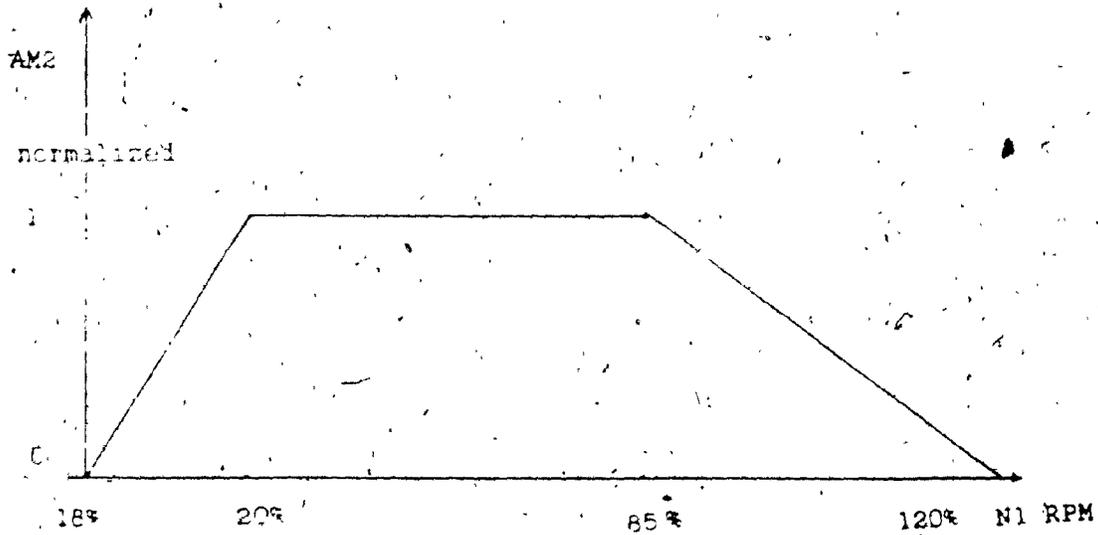
WNAMP amplitude of white noise

ENGWHITE tuning constant

A flowchart of the engine section of the program is presented in figures 5.9, 5.10, 5.11



• FIGURE 5.4 Amplitude Model Approximation - AM1 •



• FIGURE 5.5 Amplitude Model Approximation - AM2 •

• FIGURE 5.5 Amplitude Model Approximation - AM2 •

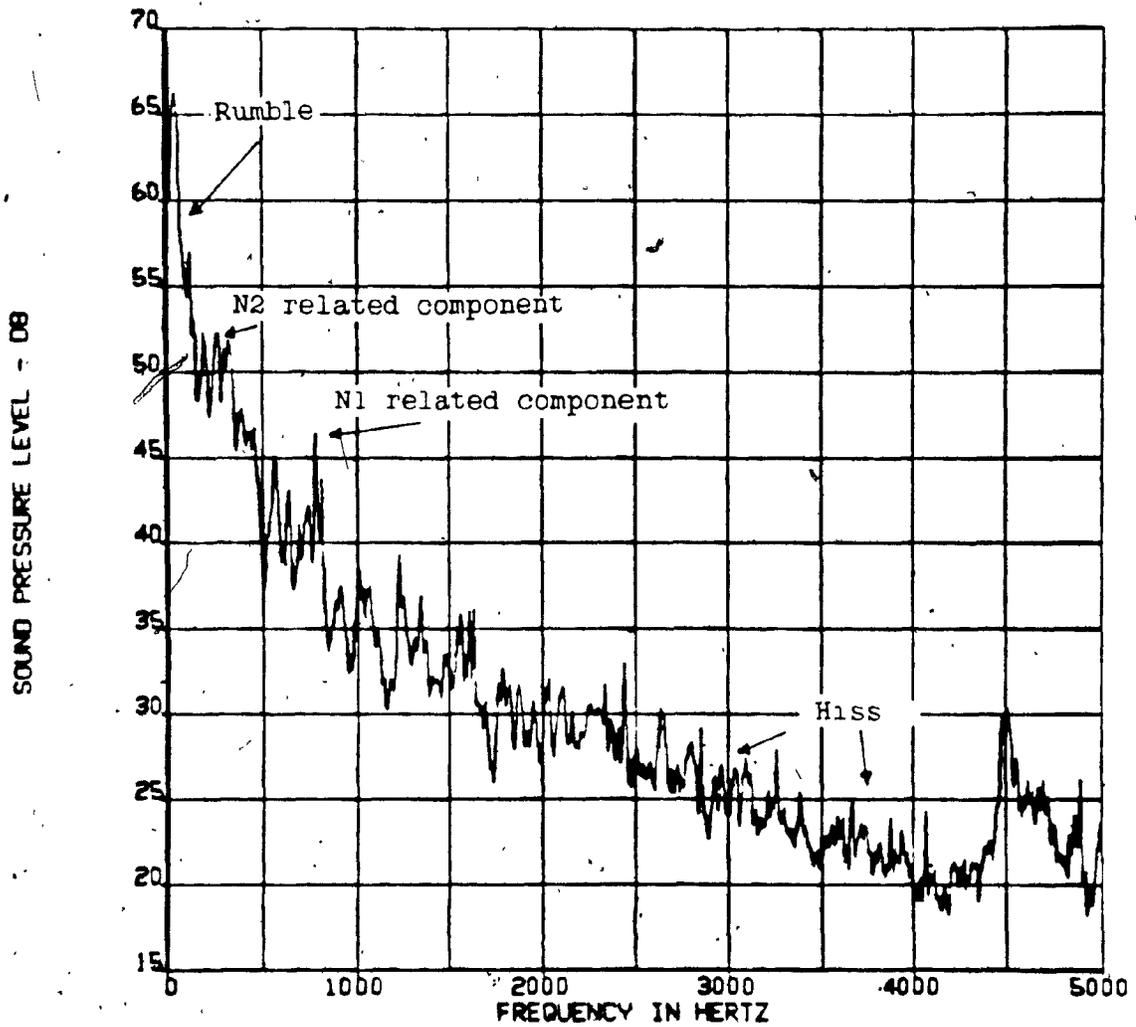


FIGURE 5.6 Engine 1 at Idle

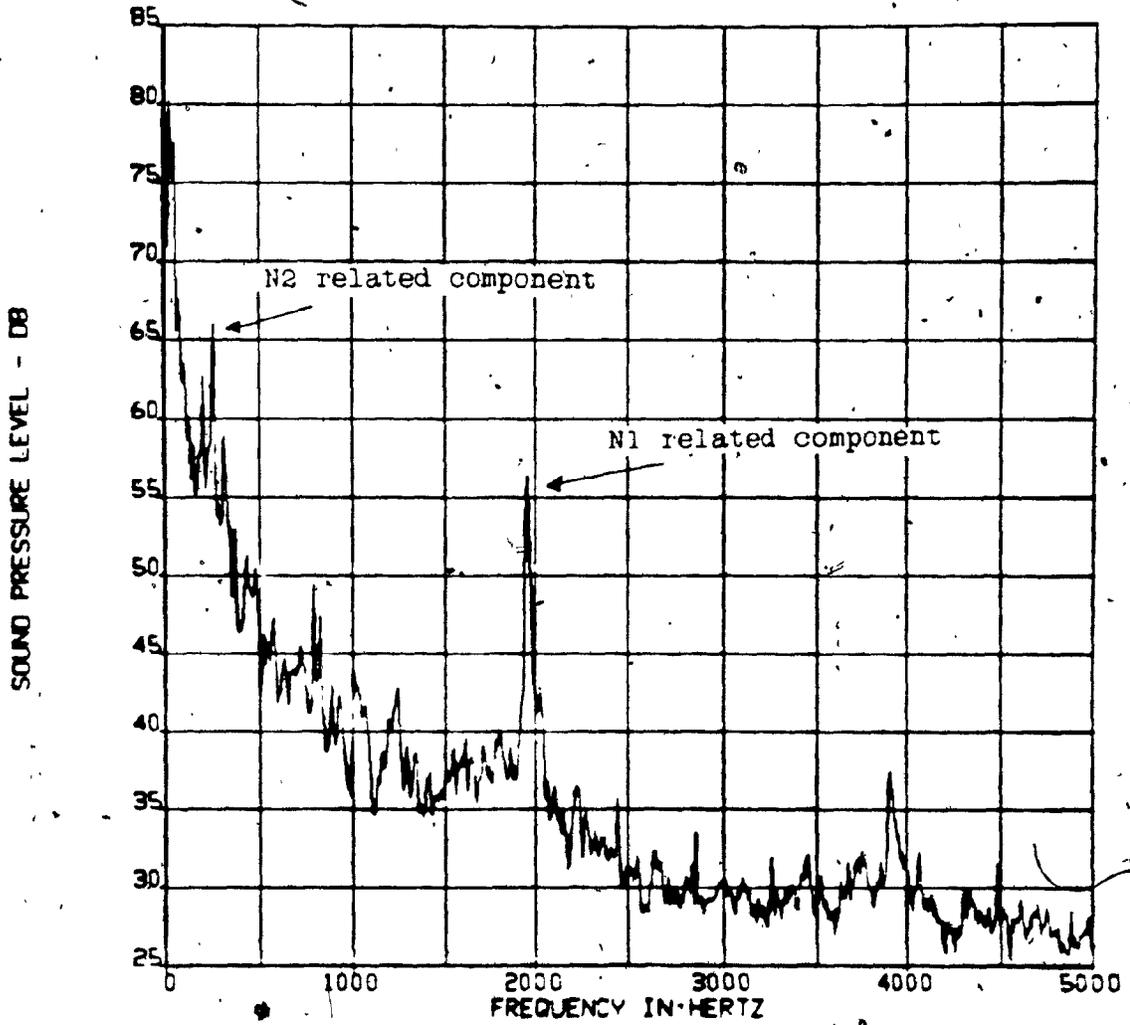


FIGURE 5 7 Engine 1 at Midpower Setting

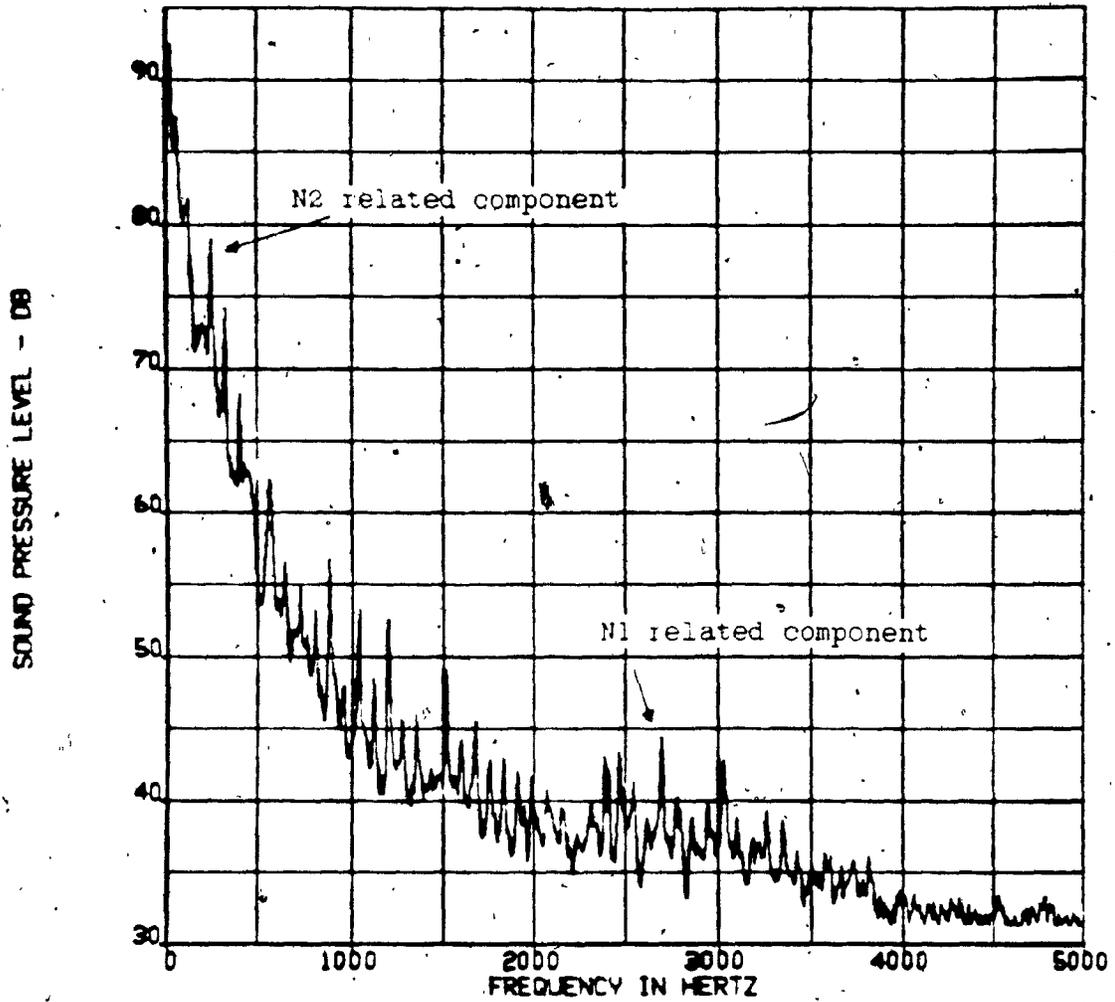


FIGURE 5.8 Both Engines at Take Off Power

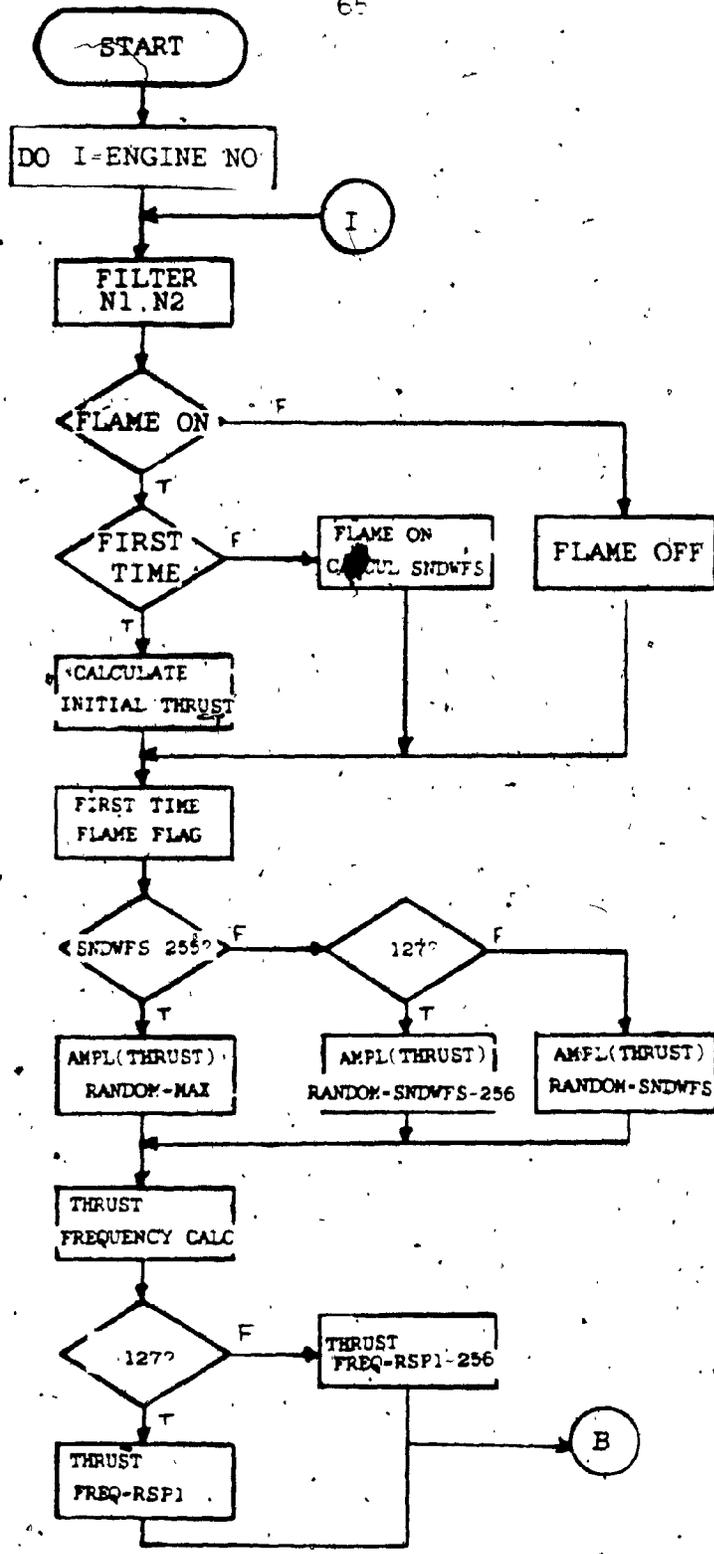


FIGURE 5.9 Engine Program Flowchart

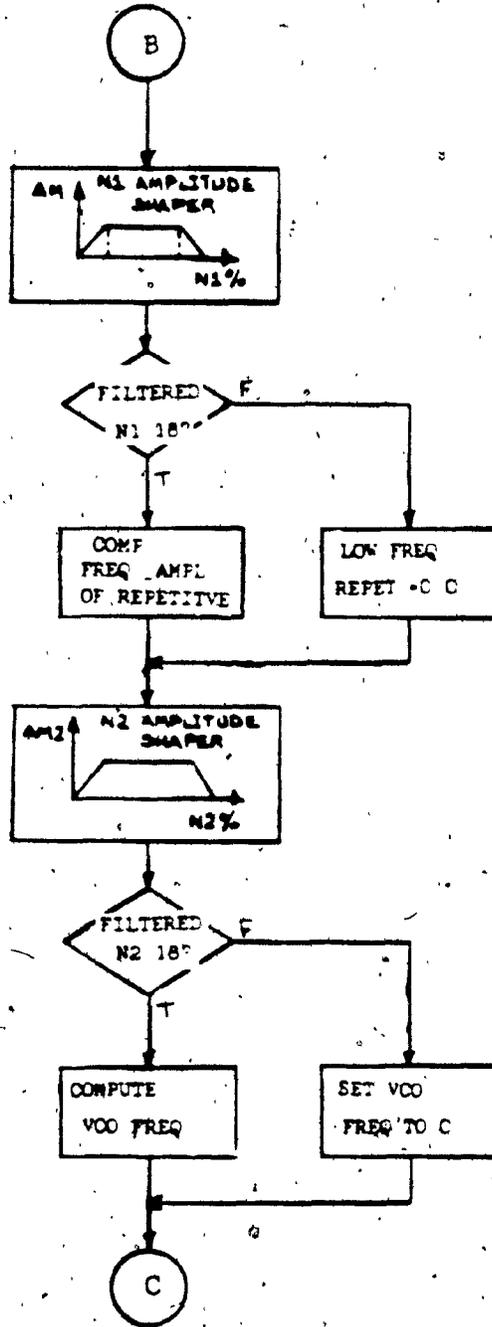


FIGURE 5 10 Engine Program Flowchart

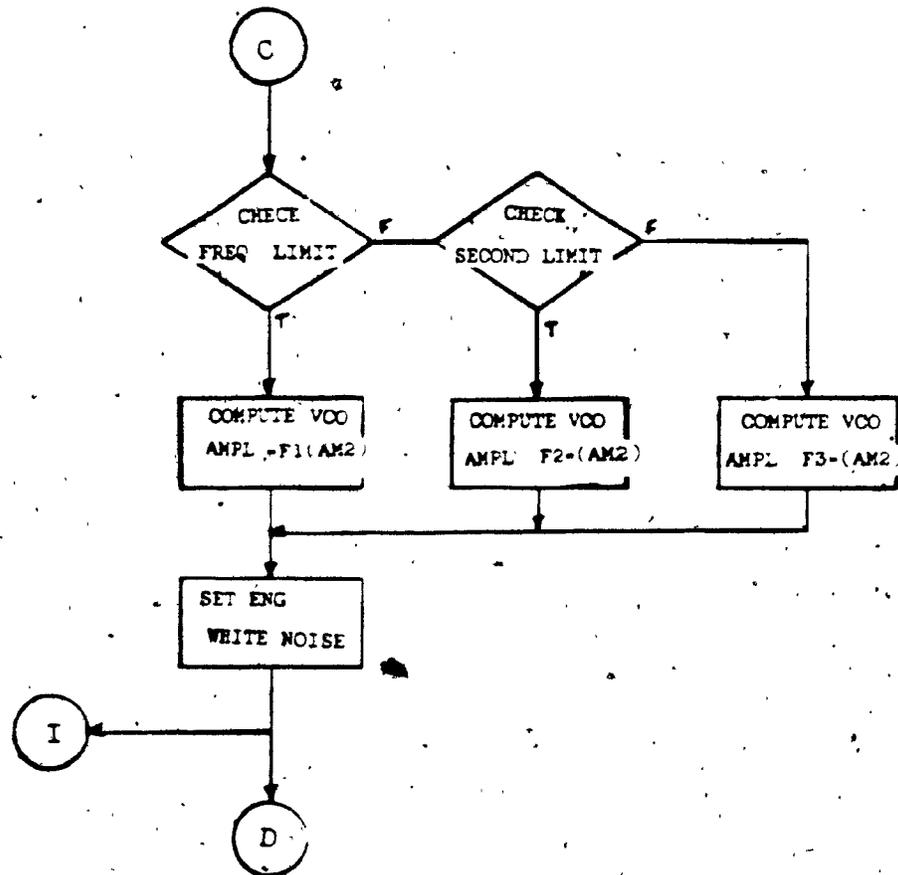


FIGURE 5 11 Engine Program Flowchart

5.3 AUXILLIARY POWER UNIT (APU)

This section computes the high frequency components for the APU sound generation.

5.3.1 System Description

The APU sound is composed of two main components

a. A high frequency component which is related to the APU revolutions per minute level. This component follows the curve shown in fig. 5 12. [7]

b. A low frequency term which corresponds to thrust noise. This sound is hardly audible, and is usually not simulated at all.

Observing the APU frequency spectrum, we can also notice the presence of 400 Hz harmonics due to the flight instruments. [7] Refer to figure 5 13

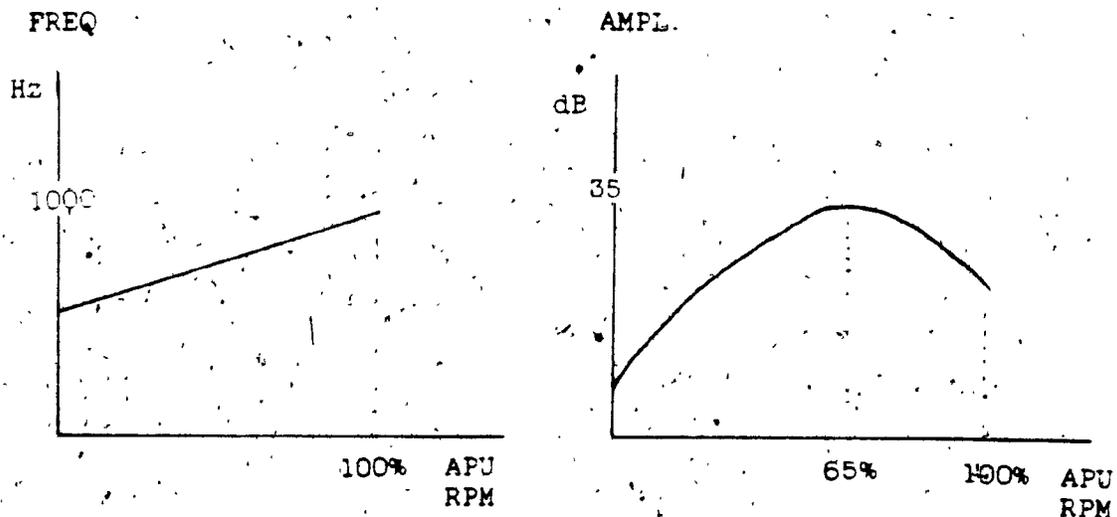


FIGURE 5 12 . APU Sound Shape

5.3.2 Program Description

The equation set used to approximate the high frequency component shape, shown in figure 5.12 is the following :

a. Amplitude

$$VCOA(1) = \text{LOG}(\text{MAX}(\text{AURPM}, 1.0)) * \text{APUAMP1}$$

for : $1 < \text{AURPM} \leq 65$

$$VCOA(1) = \text{LOG}(\text{MAX}(65. - (\text{AURPM} - 64.), 1.)) * \text{APUAMP2}$$

for : $65 < \text{AURPM} \leq 100$

equation 10

where

AURPM equivalent RPM of APU
 APUAMP1 amplitude tuning constant
 APUAMP2 amplitude tuning constant

b. Frequency

$$VCOF(1) = (\text{AURPM} * \text{RPM} + \text{APUFRE}) * \text{KC}$$

where

RPM calibration constant
 APUFRE frequency tuning constant
 KC a tuning constant.

The APU program flowchart is presented in figure 5.14

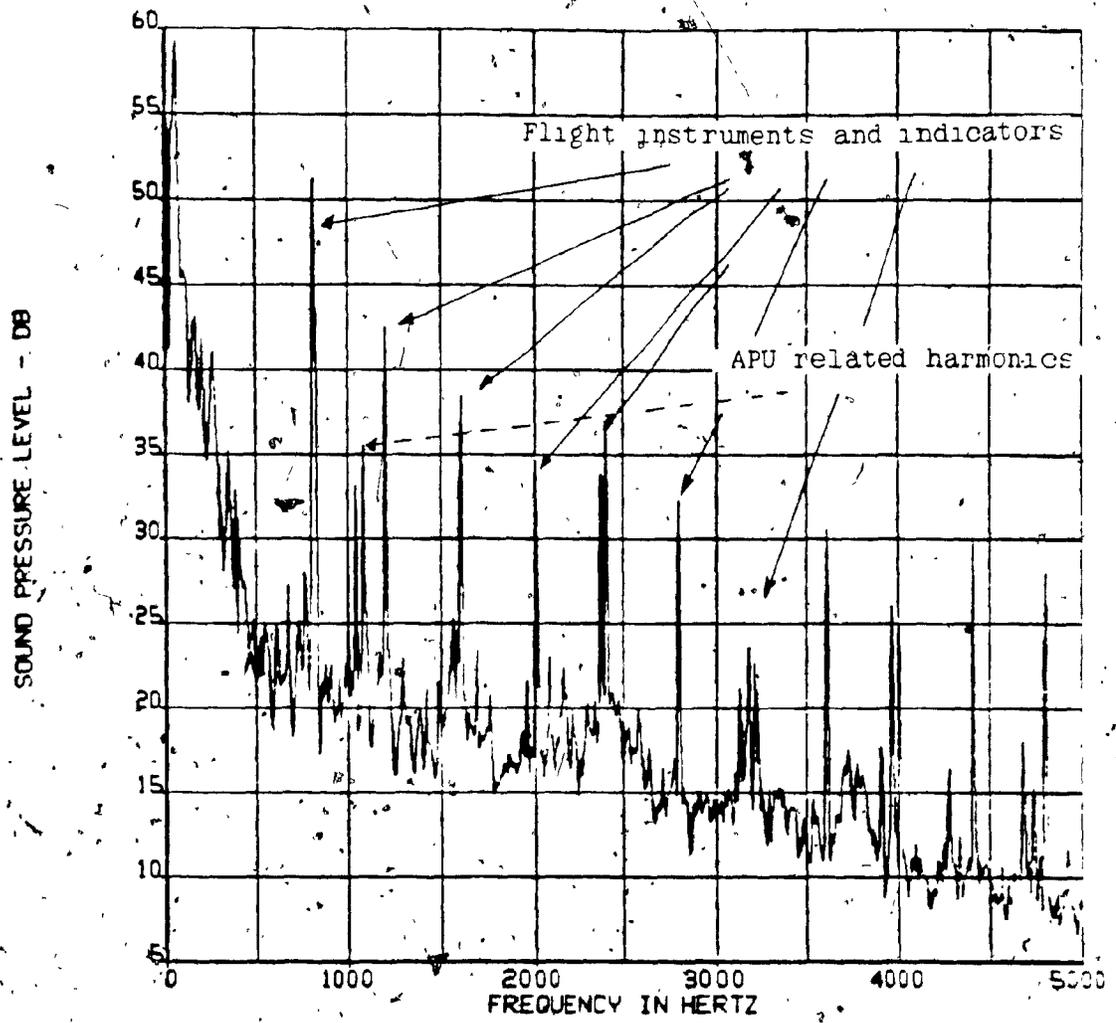


FIGURE 5.13 APU at Idle

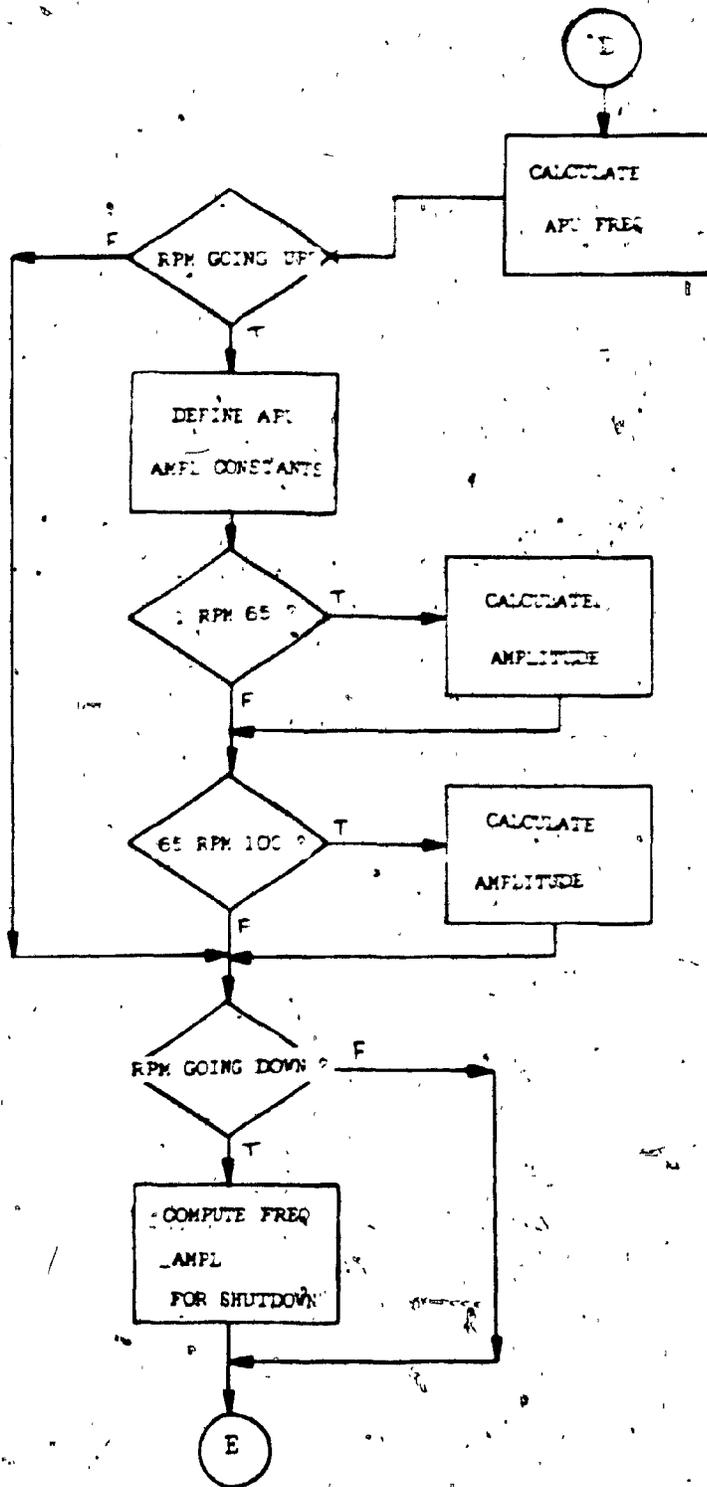


FIGURE 5.14 APU Program Flowchart

5.4 AEROPLANE NOISES PROGRAM DESCRIPTION

This part of the program computes the various airplane noises occurring inside as well as outside the cockpit. These include

Flaps and Spoilers fig. 5.17 5.18

Gear and door noise fig. 5.19

Aerodynamic noise

Rapid decompression

Air conditioning fig. 5.15 5.16

The presence of 400 Hz harmonics due to the flight instruments can be easily seen in the various graphs [7]. For example in figures 5.16 and 5.17, we can observe the discrete components at 400, 800, 1200, 1600, 2000, 2400 Hz.

5.4.1 Flaps And Spoilers

These sounds are computed as random noises. The average position of these mechanical parts with reference to the wing surface as well as the airspeed, are the main parameters for the computation [7].

The amplitude calculations for the flaps and the spoilers, respectively, are

$$\text{RANDOM08} = \text{MIN}(\text{MAX}(\text{VVE} * \text{FLAPOS} * \text{KFLAP}, 0.), .255.)$$

equation 11

$$\text{RANDOM04} = \text{MIN}(\text{MAX}(\text{CSP} * \text{VVE} * \text{SPOIL}, 0.), .255.)$$

equation 12

where

FLAPOC average flap position variable degrees
VVE equivalent air speed knots
SPOF average spoiler position variable degrees
EFLAP constant for average flap position
SPOIL tuning constant

The frequency is set to 255 Hz for flaps and 100 Hz for
spoilers

5 4 2 Gear And Door Hiss

Landing gear hiss is a function of the position of the
gears and of the doors. It also depends as most of the
aerchiss noises on the aircraft speed. These sounds will be
computed as random noises [7].

The equation set is as follows:

RSP2 = 0 for VVE = 60
= (DORNOS + AGGPL(3) * 0.5 *
(AGGPL(1) + AGGPL(2)))
(VVE - 60) * GEARHISS elsewhere
RANDOM06A = MIN(MAX(RSP2, 0.), 255.) equation 13

where

RSP2 temporary variable

- AGGFL position of the 3 landing gears 0 to 1
- VVE equivalent air speed knots
- GEARHISS tuning constant for the landing gear
- DORNOS equivalent nose door position 0 to 1

5 4 3 Aerodynamic Hiss

The noise is produced by three white noise generators. One generator is used to simulate the sound generated by the cockpit noise and the other two are used to simulate the sideslip hiss.

The noise is a function of speed, altitude, and cabin pressure [7]. The computations are done as follows:

1. Aerchiss

$$WNAMP(12) = \text{MIN}(\text{MAX}(VVE \cdot 3 \cdot \text{VOFFSET}), (\text{ALTITU} \cdot \text{VHH}) \cdot \text{AEROHISS} \cdot 0.1, \text{HISLMT})$$

equation 14

where

- WNAMP amplitude of the white noise output
- ALTITU altitude tuning constant
- VHH equivalent pressure altitude variable (feet)
- VOFFSET tuning constant
- AEROHISS tuning constant
- HISLMT tuning constant

11 Sideslip hiss

The sideslip hiss produces small variation on the directionality of the aerodynamic noise. The amplitude calculation uses the parameter VBETA which is the angle of airplane axis to the direction of flight

$$\text{AEROL} = \text{MIN}(\text{ABS}(1-\text{VBETA}) * (\text{WNAMP} / 12) * \text{SLIP1}, 30000)$$

equation 15

$$\text{AEROR} = \text{MIN}(\text{ABS}(1-\text{VBETA}) * (\text{WNAMP} / 12) * \text{SLIP2}, 30000)$$

equation 16

where

| | |
|-------|--------------------------|
| AEROL | temporary variable |
| AEROR | temporary variable |
| VBETA | sideslip angle (degrees) |
| SLIP1 | tuning constant |
| SLIP2 | tuning constant |

The contributions of the sideslip hiss, left and right, to the white noise output, are taken into account later in the computation of Rain and Hail.

5.4.4 Rapid Decompression

This condition is generated by a sudden air flow into the cockpit cabin. A voluntary depressurization by the crew, or a window malfunction (window opens in flight), bring the system into this state.

Decompression is dependent on the actual cabin pressure and is simulated by two white noise generators. The effect lasts as long as the differential pressure is greater than zero. The equation set is as follows:

$$\text{RAPDEC1} = \text{MIN}(\text{DTPDI} \cdot \text{PRESS.} / 31000, 0) \quad \text{equation 17}$$

$$\text{RAPDEC2} = \text{RAPDEC1} \quad \text{equation 18}$$

where

RAPDEC1 temporary variable

RAPDEC2 temporary variable

PRESS. is a tuning constant

DTPDI cabin differential pressure (PSI)

As mentioned in the previous section, the white noise contribution of the rapid decompression are taken into account later.

5 4 5 Air Conditioning

This sound is generated by the Gasper fan and the air-conditioning packs. It is a controlled air rush into the cockpit cabin. The simulation parameter is the average cabin air flow [7]

The following equations are used:

$$\text{Gasper fan: } \text{RSP1} = \text{GASAMP} \cdot \text{GASUP} \quad \text{equation 19}$$

where

GASAMP gasper fan inflow variable (LB/MIN)

RSP1 temporary variable

GASUP tuning constant

Packs $RSP2 - DNWCC \cdot AIRAMP$ equation 20

where

RSP2 temporary variable

AIRAMP pack amplitude constant

DNWCC cabin inflow variable (LB MIN)

The total air conditioning noise is then a summation of the packs and gasper fan computations, and their noise contribution is considered later.

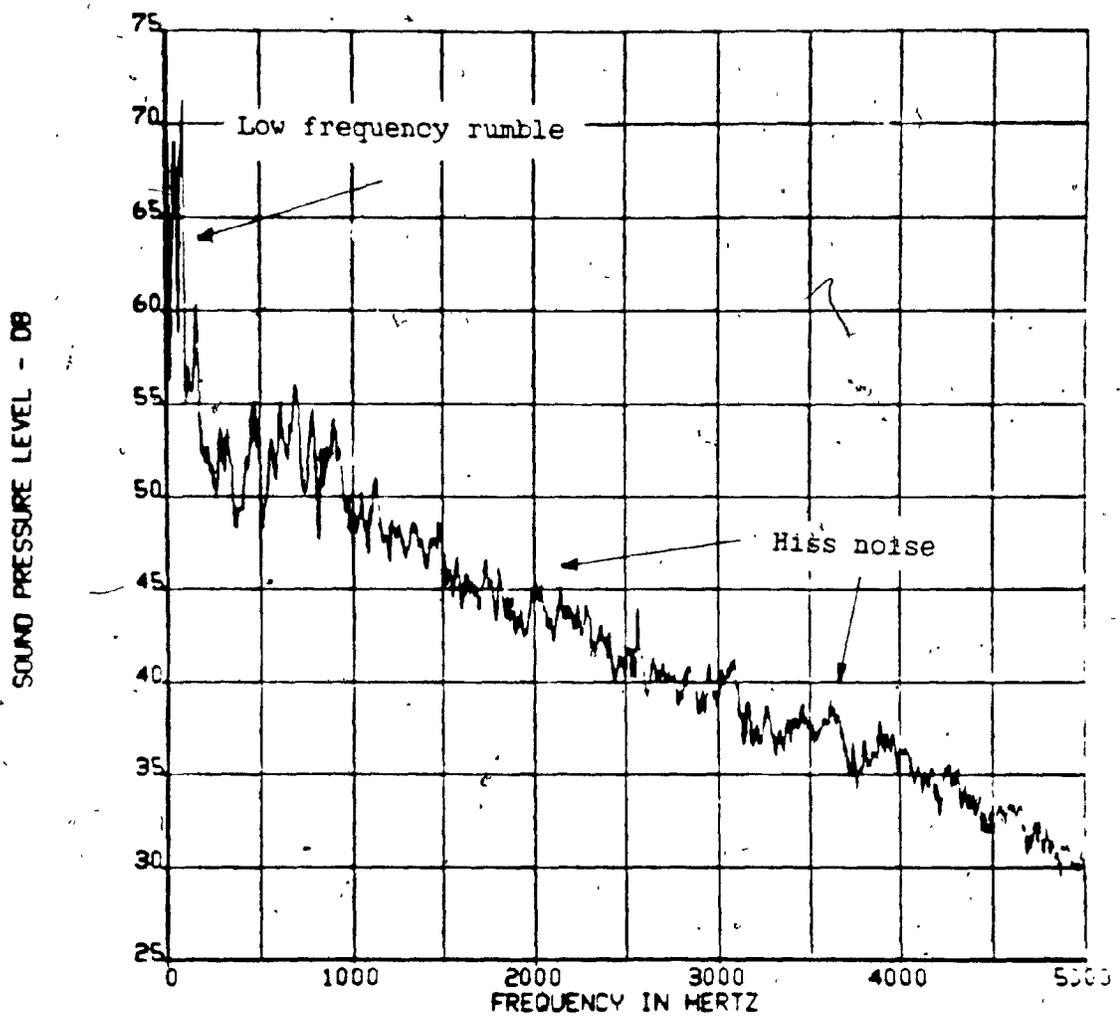
$$AIRCON = RSP1 - RSP2$$

where

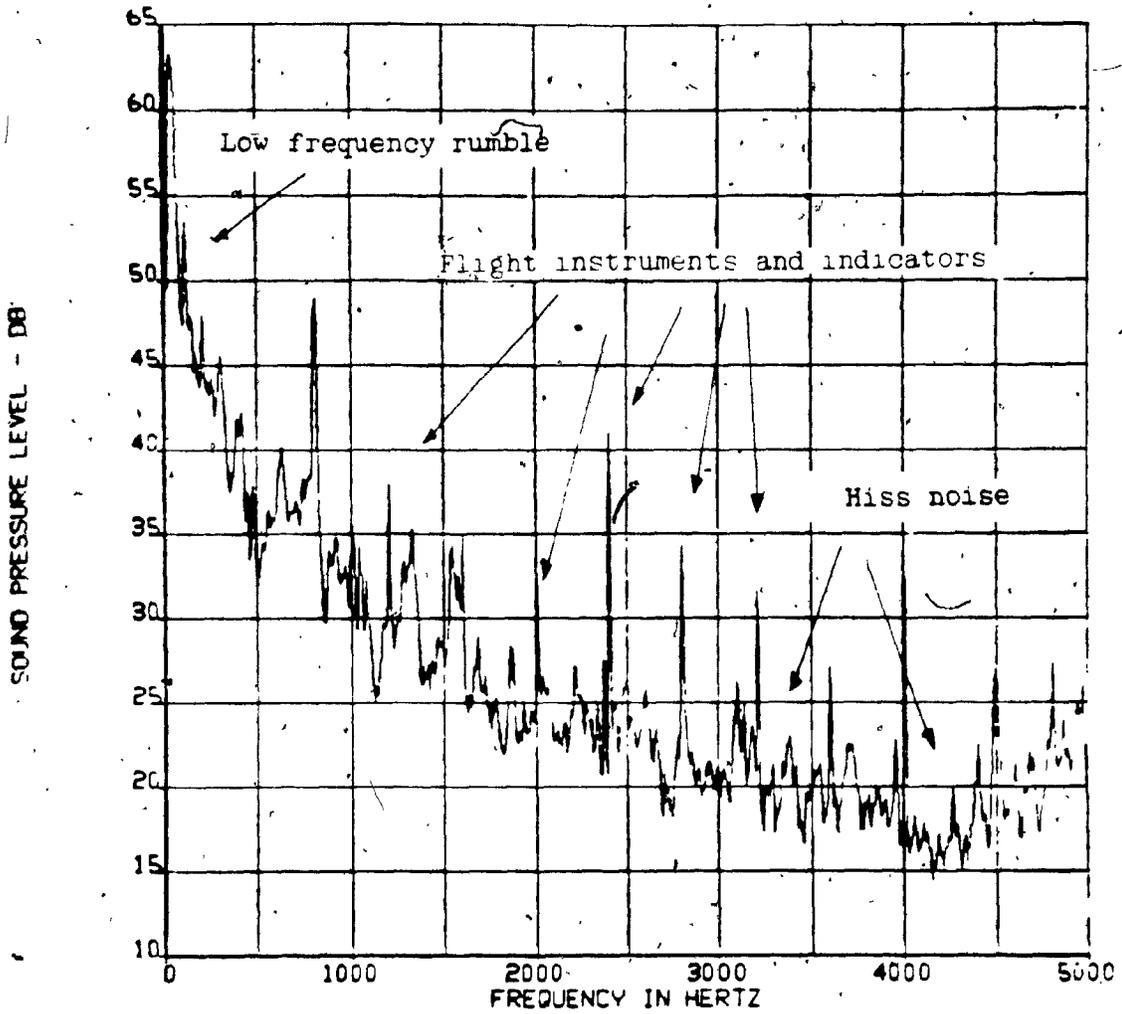
AIRCON air conditioning temporary variable

The flowcharts for the aerohiss noises are presented in figures 5.20, 5.21, 5.22.

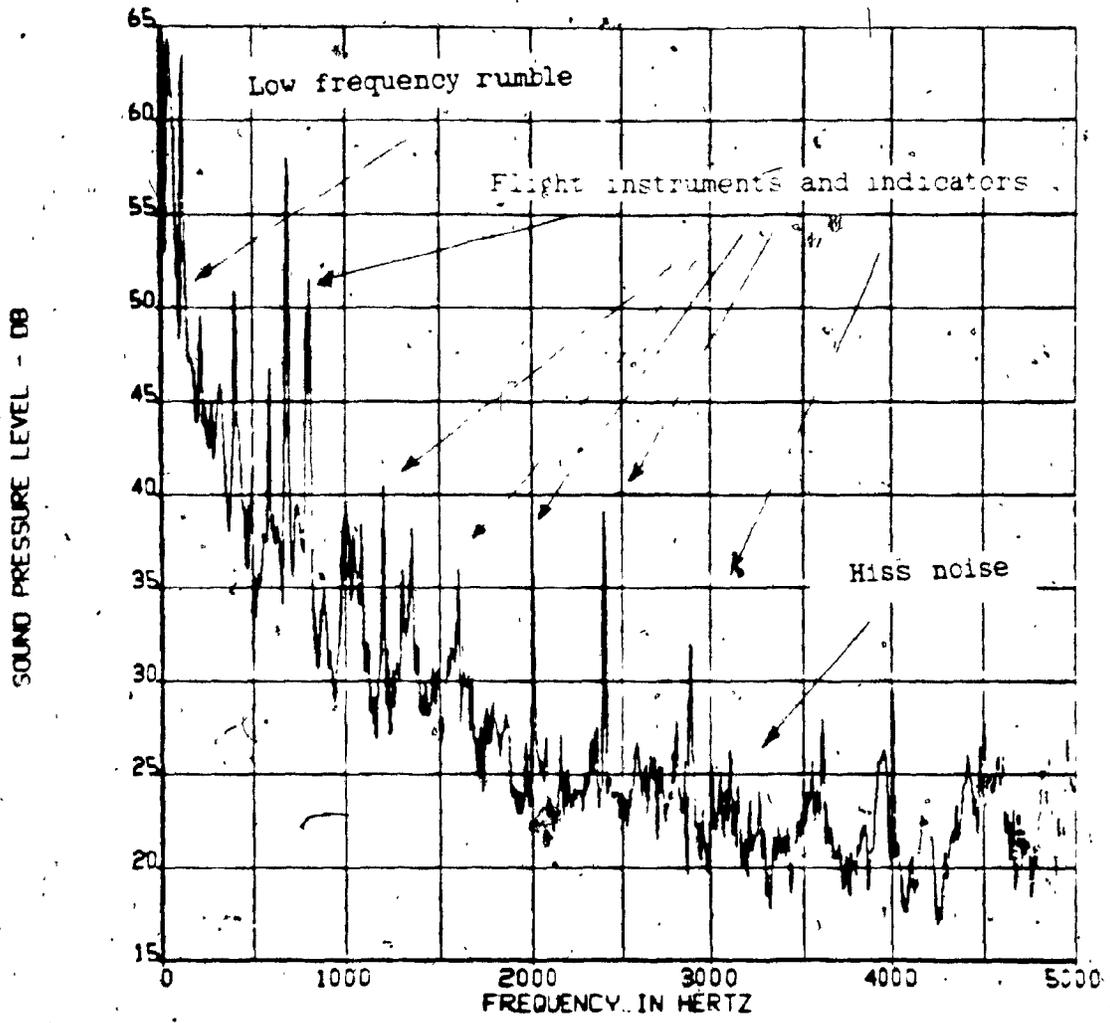
Comparing figures 5.15 and 5.16, we can see how the sound produced by the packs, under certain conditions, masks the discrete frequency components present in the cockpit.



*FIGURE 5.15 Packs On, Gasper On *



*FIGURE 5.16 Gasper fan only On *



*FIGURE 5.17 Flap Extension *

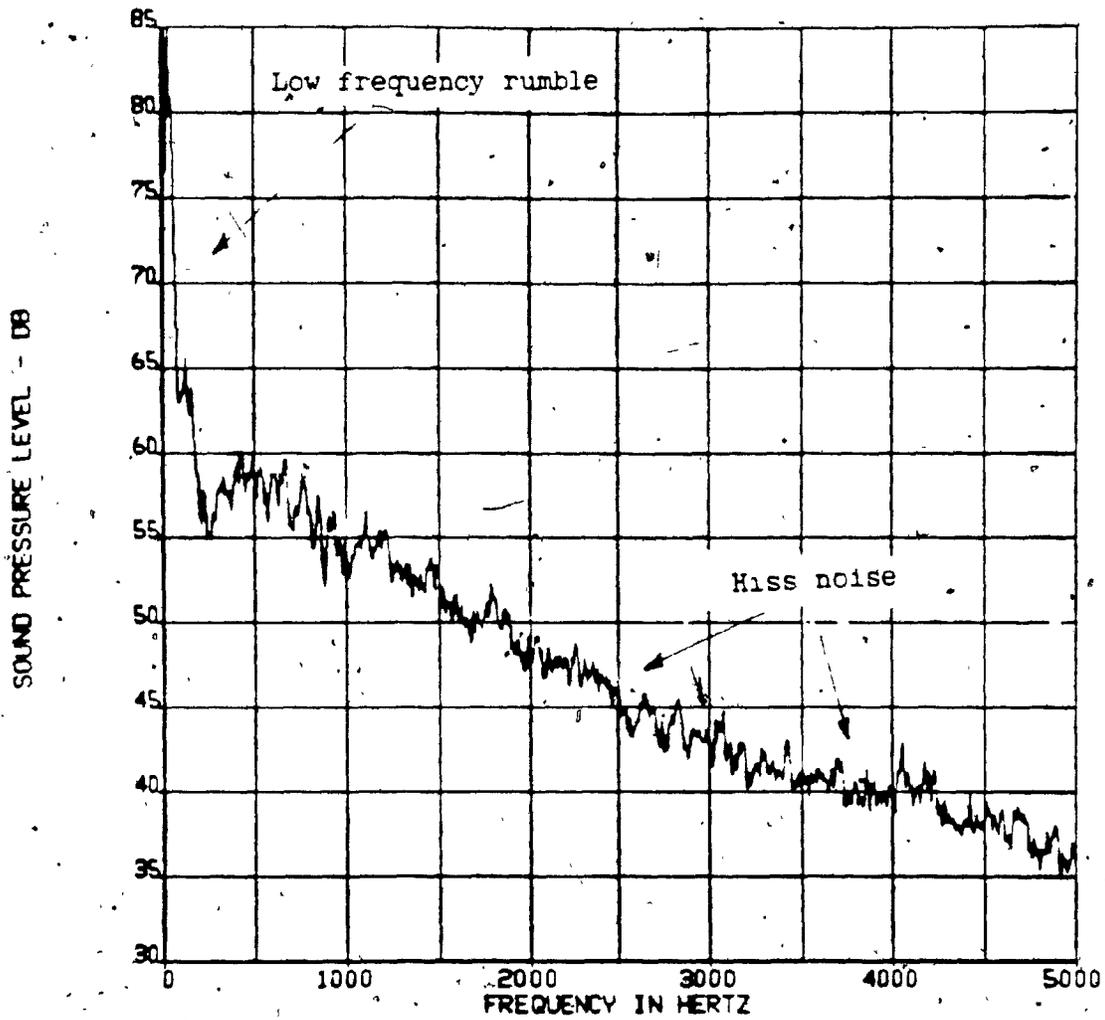
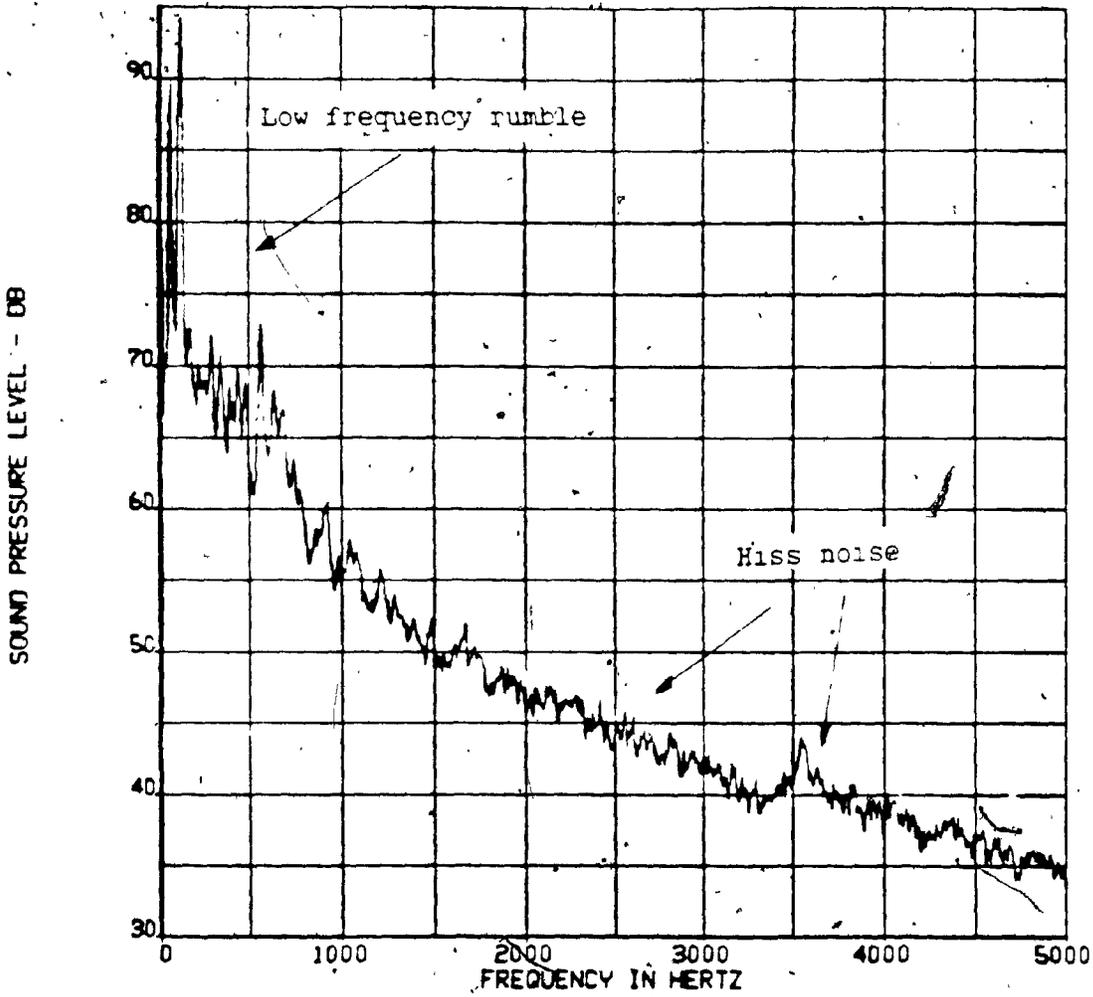
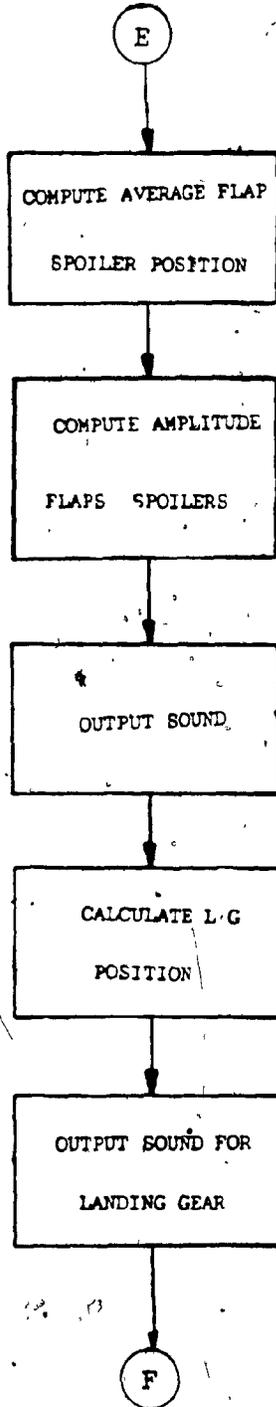


FIGURE 5.18 Spoiler Extension



*FIGURE 5.19 Landing Gear Extension *



*FIGURE 5.20 Aeronoiseis Program Flowchart *

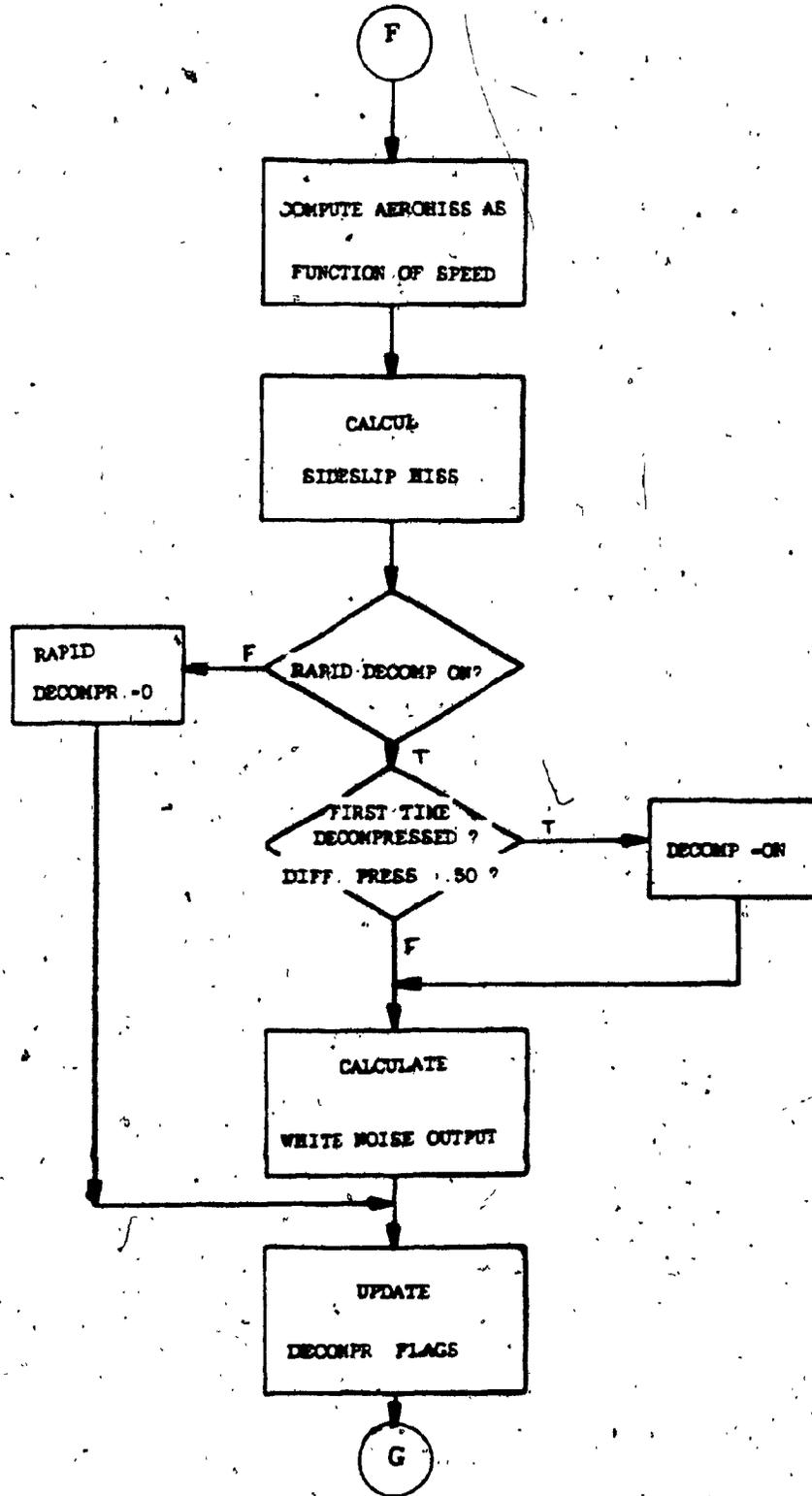
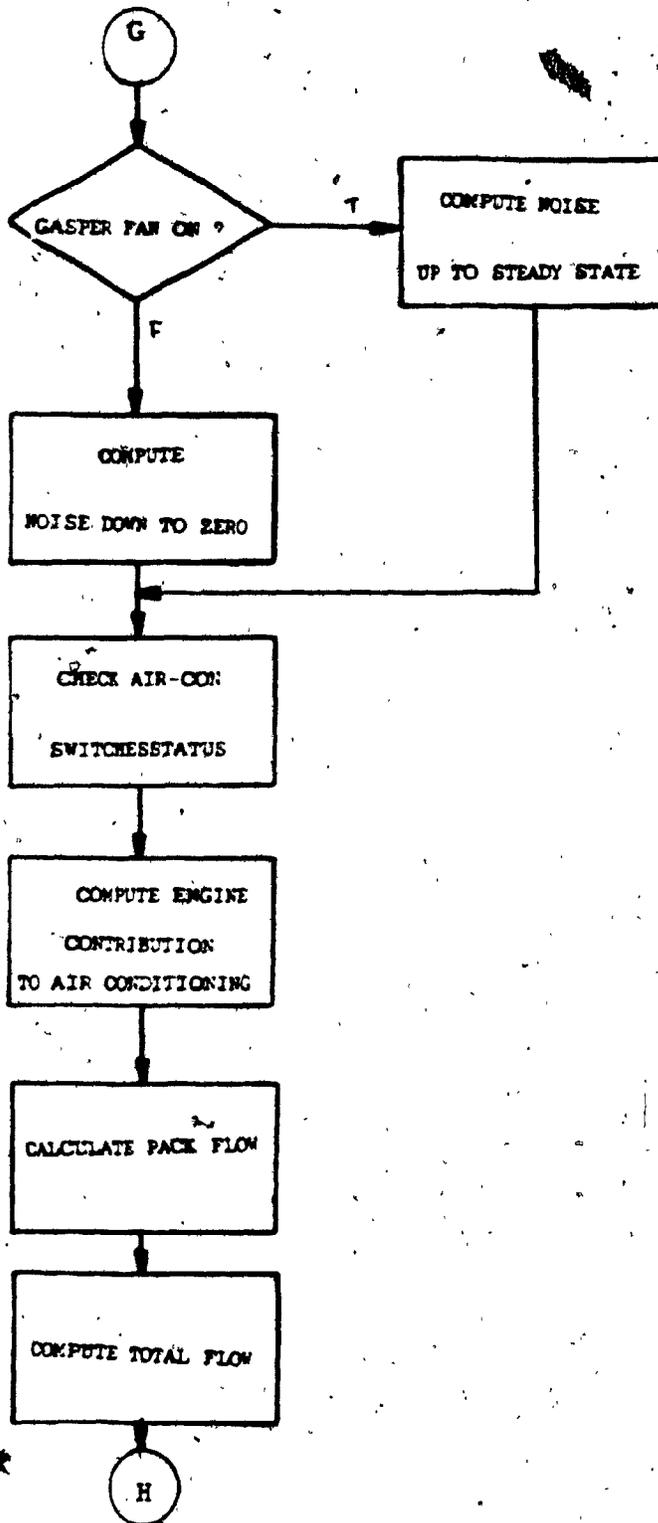


FIGURE 5.21 Aeronoise Program Flowchart



*FIGURE 5.22 Aeronoise program Flowchart *

5.5 Windshield Wipers

This section simulates the sounds which are generated by the mechanical motion of the windshield wipers, located in front of the pilot and the copilot. [7]

5.5.1 System Description

The sound is generated by the friction of the wiper slab rubber on the windows. It is mainly composed of a continuous component, which is frequency dependent on the wiper selected speed: low, high, park.

When the wipers are operated under rain conditions, the windshield surface is wet and as a result there is less friction between the wiper slab and the window. This condition reduces in effect the continuous sound in amplitude, it adds though a high frequency component to it. The voltage controlled oscillator 12. is used to simulate this effect.

a. The amplitude of the wipers sound, depends on the number of wipers in operation. It is maximum when both wipers are on, 75% when one wiper is operating, and zero when both wipers are off.

b. The frequency is set through a table containing the frequency of slabs depending upon the selector position.

The equations then for amplitude and frequency are respectively :

$$\text{CONTINO6}(4) = \text{WVAMP} \quad \text{equation 21}$$

$$\text{CONTINO6}(1) = \text{WVRPM}(I) \quad \text{equation 22.}$$

where

I selected speed constant

WVAMP wiper amplitude constant

WVRPM wiper frequency constant

c. Rain effect equations

The amplitude and frequency of the VCO is computed as follows:

$$\begin{aligned} \text{VCOA12} &= \text{WVRAIN} * \text{ABS}(\text{SIN}(\text{YTSIMT} * \text{FPX})) \\ &+ \text{WVRAIN1} \end{aligned} \quad \text{equation 22}$$

$$\text{VCOF12} = \text{VCOA12} \quad \text{equation 23}$$

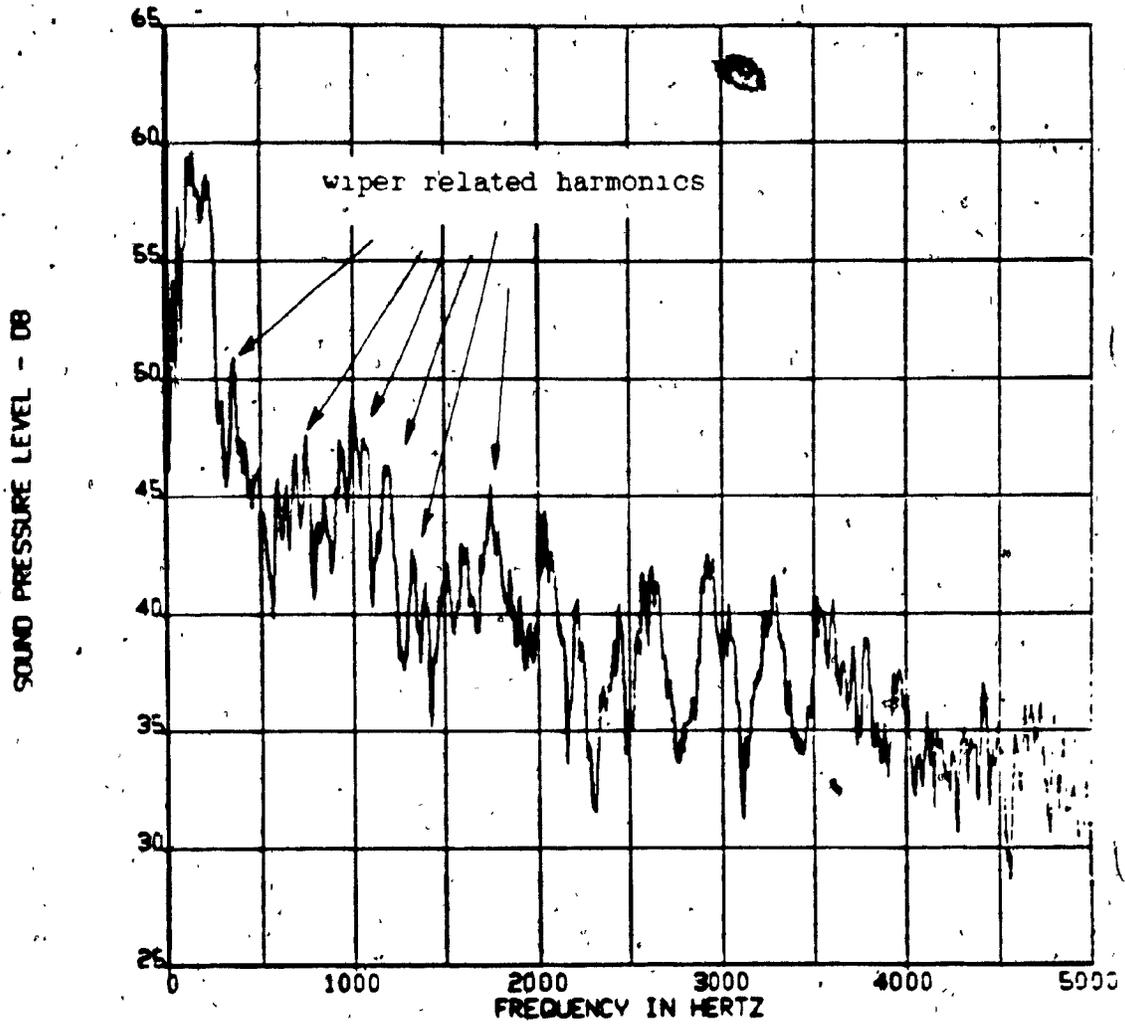
where

YTSIMT simulator timer variable (sec)

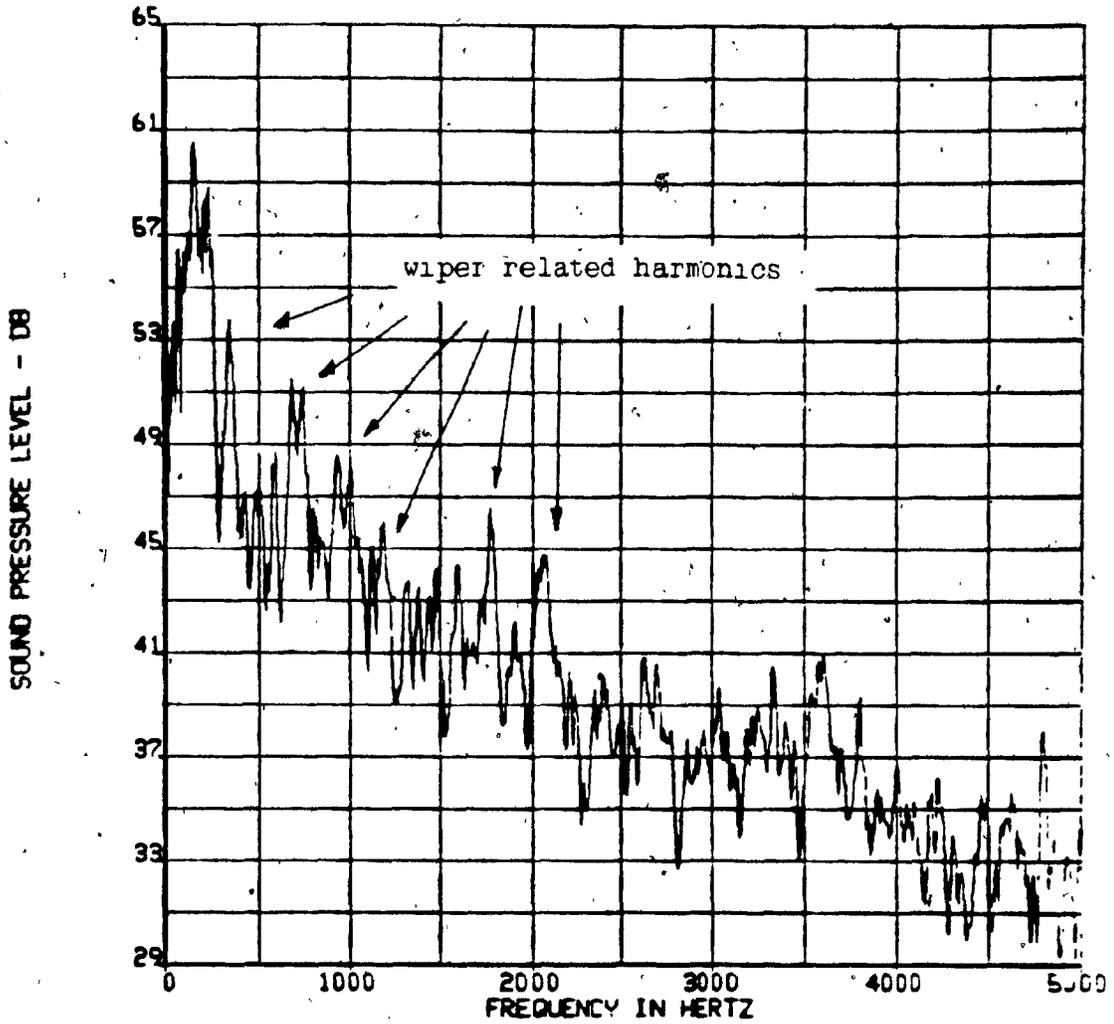
WVRAIN1,2 rain effect constants

FPX modulation factor constant (deg/sec)

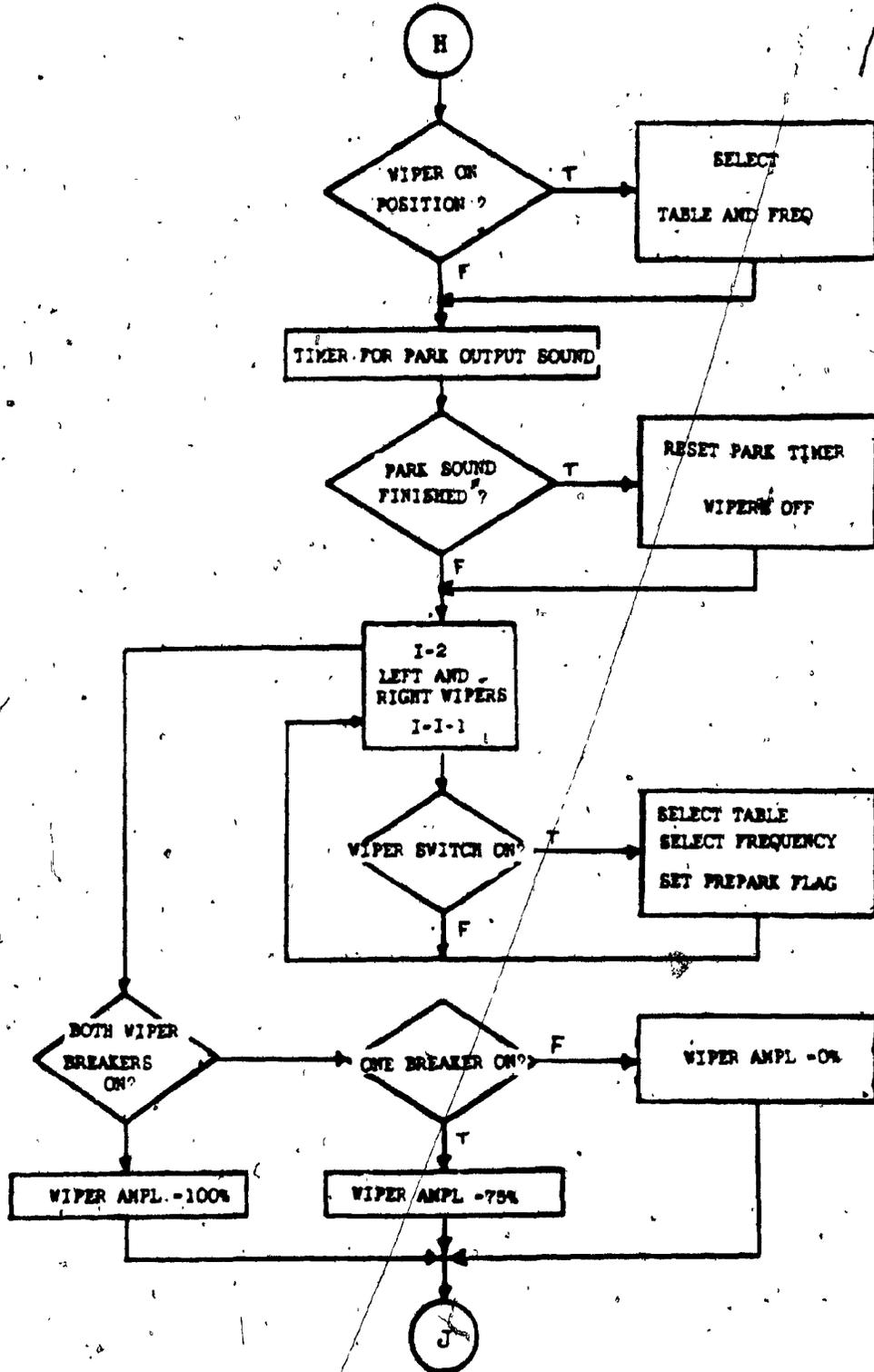
The flowchart for the windshield wipers coding is given in figures 5.25, 5.26 . Figures 5.23 and 5.24 present the frequency spectra at two speeds of these sounds. The indicated harmonics are stored in two tables and are referenced by the CONTINO6 parameters.



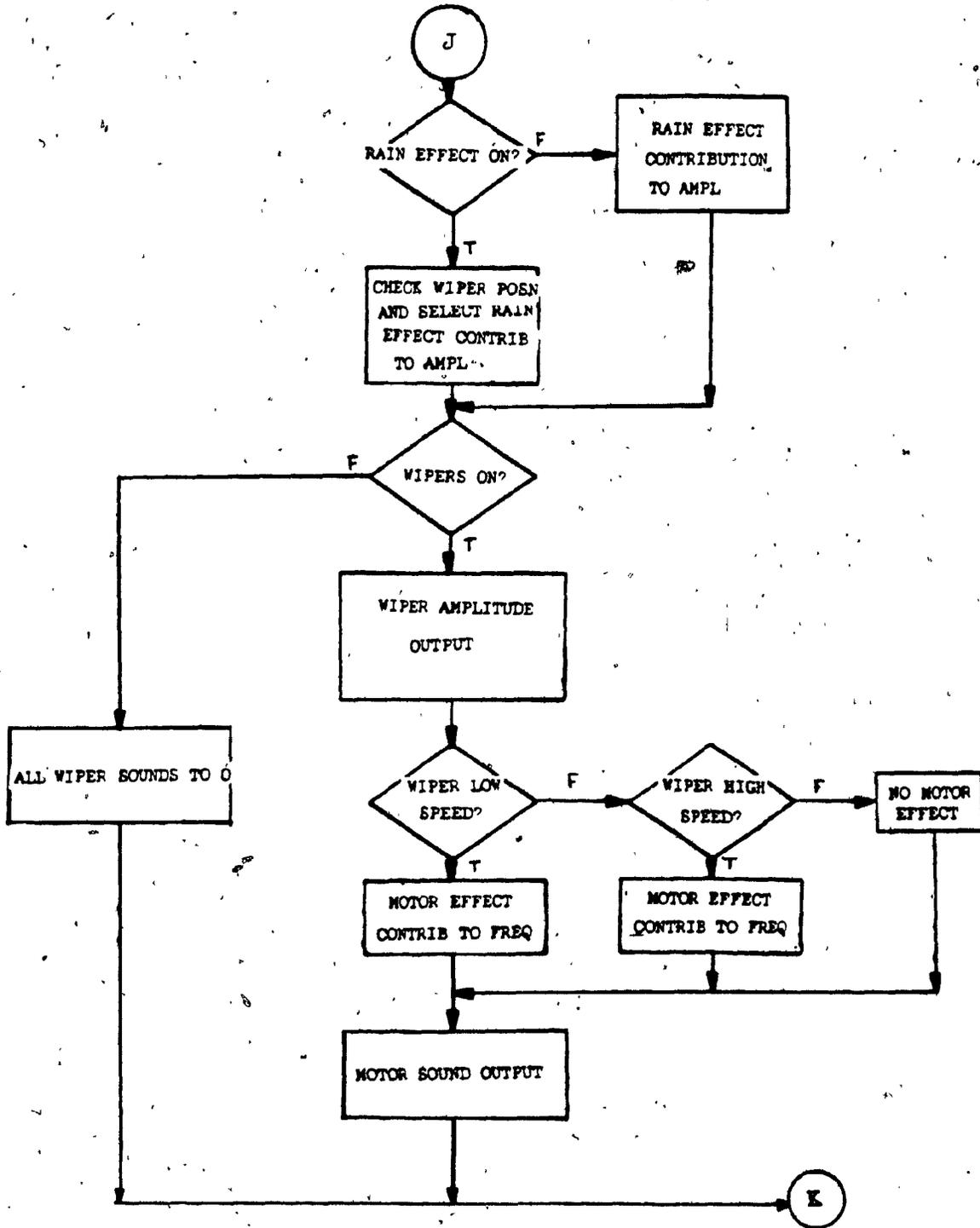
*FIGURE 5.23 Windshield Wipers-Low speed *



*FIGURE 5.24 Windshield Wipers-High speed *



*FIGURE 5.25 Windshield Wipers Program Flowchart *



*FIGURE 5.26 Windshield Wipers Program Flowchart *

5.6 Runway Rumble

In this part of the program the rumble sound which is produced by the aircraft while on runway is simulated.

5.6.1 System Description -

The following sounds are simulated: The rumble sound generated during take-off and landing, and the squeal sound at the moment of touch down. Three sound components are used for the simulation of this effect: a repetitive, a random and a high frequency waveform. The runway roughness is also taken into account, although this effect is produced in a more realistic way by the motion program.

5.6.2 Program Description -

The main parameter taken into consideration is the nose gear compression. This is used to vary the amplitude of the sound that is simulated. The frequencies of the continuous and random waveforms are kept constant.

The equation sets for the amplitude are formed as follows:

$$\text{CONTINO7(4)} = \text{MIN}((\text{RSP1} + \text{AHPOS13} + \text{ABS}(\text{VTHED})) * \text{RUMBLE1} \\ \text{255}) \quad \text{equation 24}$$

$$\text{RANDOMO7(1)} = \text{MIN}((\text{RSP2} + \text{ABS}(\text{VTHED})) * \text{RUMBLE2} \\ \text{255}) \quad \text{equation 25}$$

where

RUMBLE1 tuning constant
RUMBLE2 tuning constant
RSP1, RSP2 equivalent gear compression variables (ft/sec)
AHPOS13 front wheel skidding variable (number)
VTHED euler wheel angle (degrees)

The squeal sound is simulated using VCO 1 and 4. The frequency of the VCO's at touch down change according to the gear compression rate. The computation is done as follows:

a. Modulated frequency at touch down :

$$VCOF(I*3 - 2) = VCOF(I*3 - 2) * RSP1 * TSQUEAL1 \quad \text{equation 26}$$

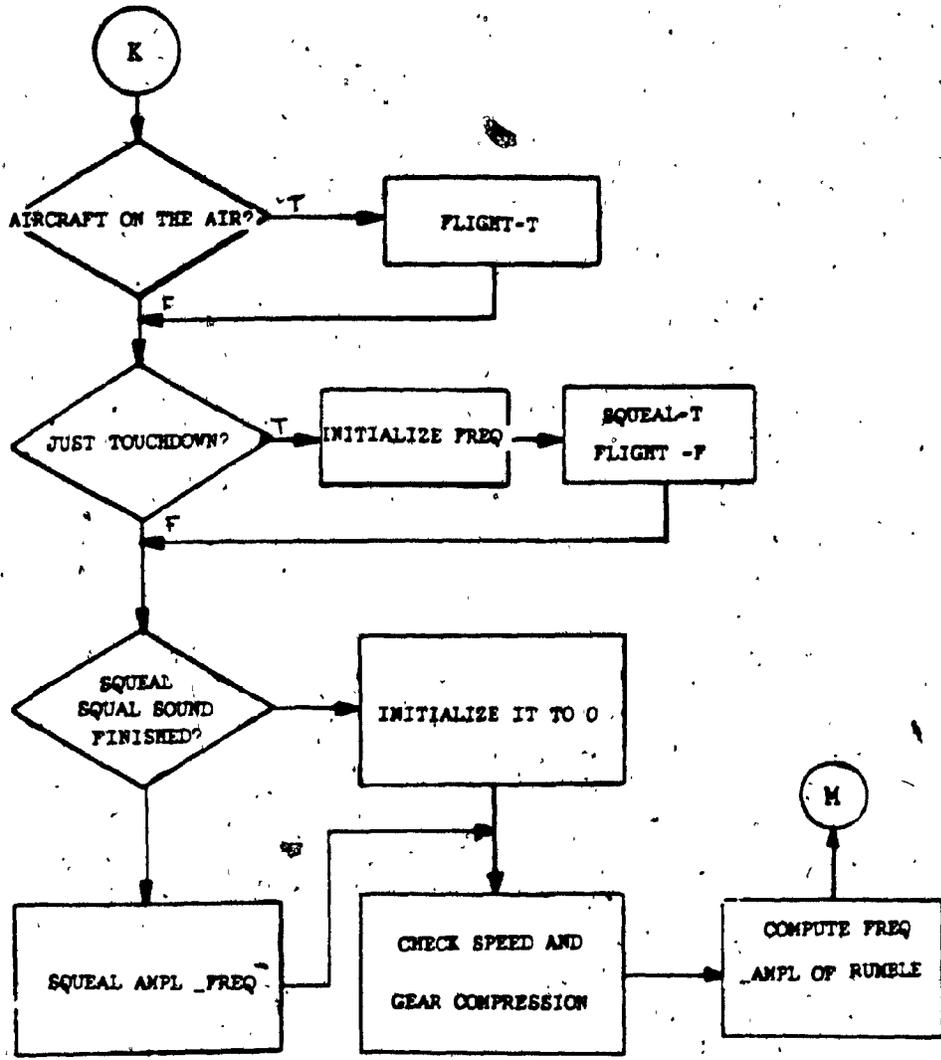
b. The amplitude is computed as follows:

$$VCOA(I*3 - 2) = TSQUEAL2 \quad \text{equation 27}$$

where

I varies from 1 to 2
TSQUEAL1 frequency tuning constant
TSQUEAL2 amplitude tuning constant

The flowchart is presented in figure 5.27



*FIGURE 5.27 Runway Rumble Program Flowchart *

5.7 Bang Sounds

These sounds are usually the result of a malfunction. They are of the same muffled quality, and they differ only in the duration and the loudness of the bang. The malfunctions are either invoked by the instructor, or by themselves if the proper conditions arise.

This section then computes the amplitudes and the duration of the bang sounds listed below. The flowcharts for the coding are presented in figures 5.28, 5.29, 5.30, 5.31, 5.32.

decompression bang

engine surge

engine seizure

turbine failure

gear uplock

gear collapse

tire burst

engine light up

5.7.1 System Description -

The bang sounds will be produced using repetitive and random noise generators and they are controlled by setting up the following parameters :

BANG bang flag logical variable

BANGD distribution of sound - bottom and front

BANGL distribution of sound - left
 BANGR distribution of sound - right
 BANGARN bang amplitude variable
 BANGTIMER bang duration variable (number of iterations)
 BANGDIST variable distribution of bang.

Outputs

CONTIN08 repetitive sound for bang
 RANDOM09 random noise for bang

5.7.2 Program Description -

The malfunction flags are supplied to the sound system, and are used to initiate the bang sounds with a specified amplitude and duration. At the end of the sound if the malfunction is still on, the bang is repeated depending on the type of the malfunction. The program generates one bang at a time, and since the probability of having two bangs occurring at the same time is very small, this presents no problem at all.

5.7.3 Decompression Bang -

As discussed in the cabin decompression section, this sound consists of a bang sound followed by a rush of air flow in the cockpit. This condition is initiated by setting TF21011

flag to true. The parameters then are set as follows :

```

BANG      = .TRUE.
BANGDIST  = 'FOO' left/right speaker distribution
BANGARN   = AMP(COUNT1)
BANGTIMER = 1.

```

where

* AMP(COUNT1) amplitude tuning constant

5.7.4. Engine Surge -

The engine surge bang sound follows the fluctuations of the engine N1 rotor RPM, and it is a repetitive bang sound. The effect is turned off when the fuel flow is out, or when the engine revolutions are brought to the idle position. The effect is initiated by setting TF71101(1) (left engine), or TF71101(2) (right engine), logical variables, to true.

The computation is done as follows :

```

ENGSURG(I) = (DIFFWF(I) .GT. SURFRAC * EN1(I))
             .AND. TF71101(I)           equation 28

BANG      = .TRUE.
BANGARN   = DIFFWF(I) * SRGAMP
BANGTIMER = 1
BANGL     = ENGSURG(1)
BANGR     = ENGSURG(2)

```

where

I is the engine number
 EN1 N1 rotor RPM variable (in percentage)
 ENGSURG engine surge condition logical variable
 DIFFWEF equivalent surge fuel flow differential
 SURFRAC tuning constant
 SRGAMP tuning constant for surge amplitude

5.7.5 Engine Seizure -

Setting malfunction flags TF71111(1), and TF71111(2) to true, the instructor can initiate an engine seizure condition.

BANG = .TRUE.
 BANGL = I.EQ.1 left engine
 BANGR = I.EQ.2 right engine
 BANGARN = BANGAMP(1)
 BANGTIMER = 1

where

I the engine number
 BANGAMP(1) bang amplitude constant

5.7.6 Turbine Failure -

A similar condition as the engine seizure, initiated by setting TF71011(1) and TF71011(2) to true

BANG = .TRUE.

BANGL = I.EQ.1 left engine
BANGR = I.EQ.2 right engine
BANGARN = BANGAMP(2).
BANGTIMER = 1

5.7.7 Gear Uplock -

This sound is not a result of a malfunction, but of the locking mechanism of the aircraft's nose landing gear after take-off. Only the nose landing gear sound is computed, since it is the only one that is audible inside the cockpit.

The bang sound is computed as follows :

BANG = .TRUE.
BANGDIST = 'C' (bottom channel)
BANGARN = GEUPLAMP
BANGTIMER = 1

where

GEUPLAMP amplitude tuning constant

5.7.8 Gear Collapse -

These sounds are produced when any of the landing gears collapses. It is usually followed by a scrapping sound, or a crash condition sound. The gear collapse condition is described by the logical value of the following flags :
TF32011, TF32012, TF32013.

BANG = .TRUE.
 BANGARN = KBANG
 BANGTIMER = 1
 BANGL = COLL(1)
 BANGR = COLL(2)
 BANGD = COLL(3)

where

COLL(1) left gear collapse logical variable
 COLL(2) right gear collapse logical variable
 COLL(3) nose gear collapse logical variable
 KBANG gear collapse amplitude constant

5.7.9 Tire Burst -

This section simulates the bang sound produced by a tire burst. The condition has to be reseted before reinitiating the malfunction. Equivalent malfunction flags are TF32091(1),(2) for the left tires. and TF32091(3),(4) for the right tires.

BURST(I) = TF32091(I).AND..NOT.PREBURST(I) equation 29
 BANGL = BURST(1).OR.BURST(2)
 BANGR = BURST(3).OR.BURST(4)
 BANG = .TRUE.
 BANGTIMER = 1

where

I the tire number

BURST tire burst condition logical variable
PREBURST previous condition of tire logical variable

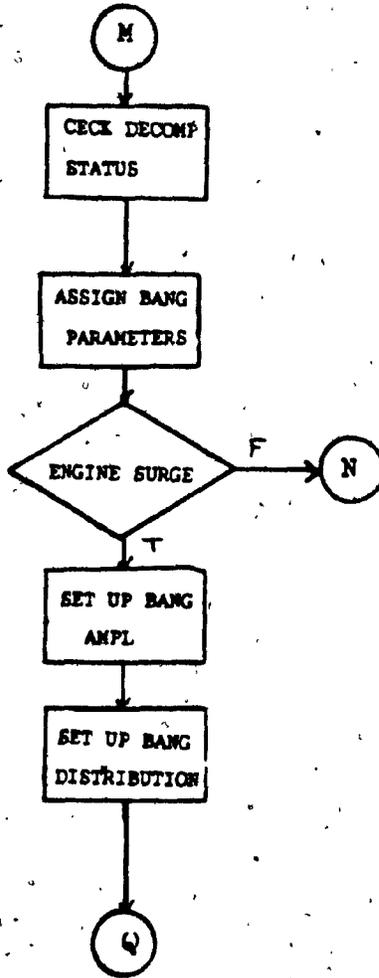
5.7.10 Engine Light-up Bang

When the engines are turned on for the first time there is a light explosion sound, which is audible inside the cockpit. This is simulated as follows :

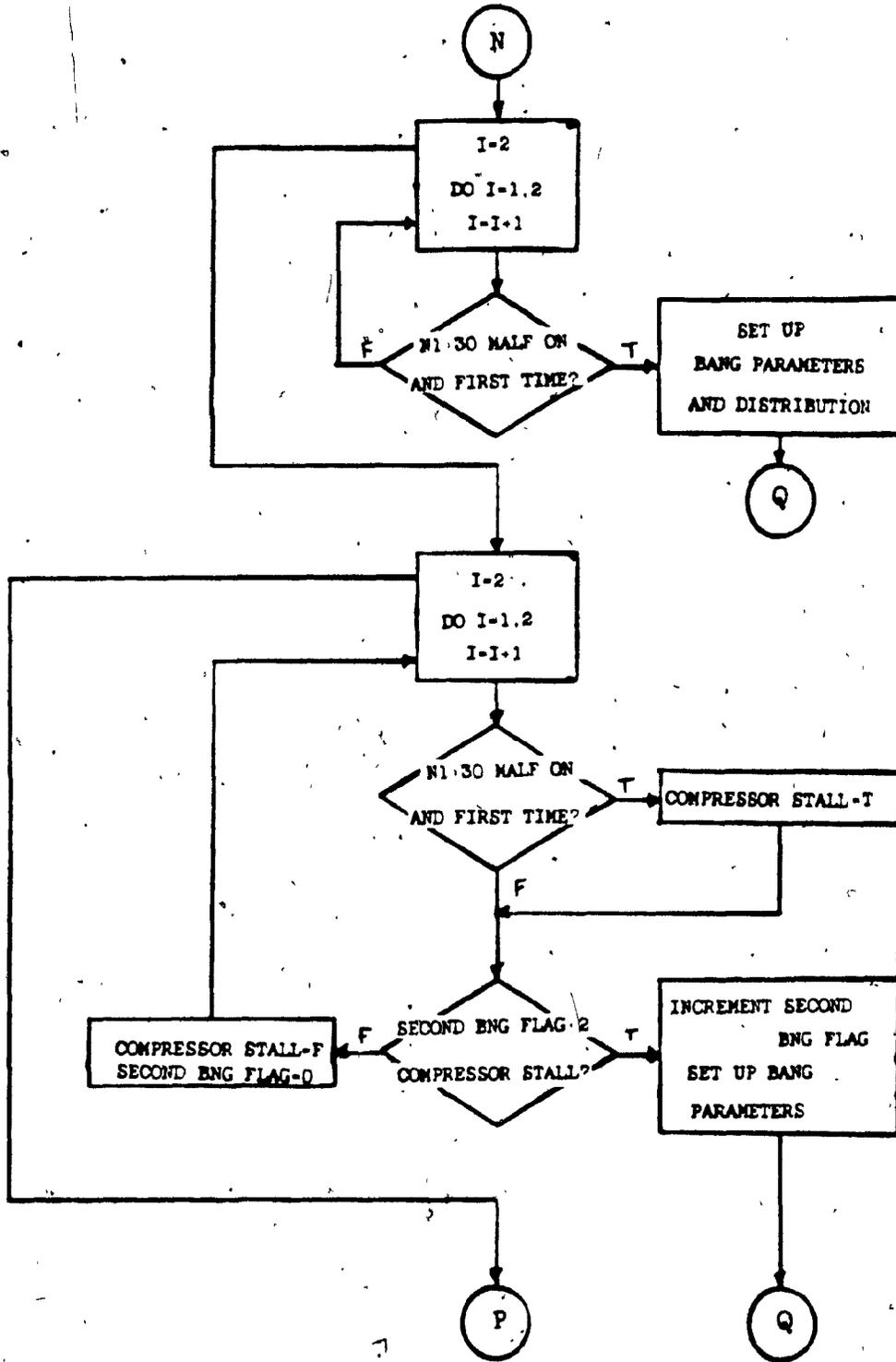
BANG = .TRUE.
BANGL = I.EQ.1 left engine
BANGR = I.EQ.2 right engine
BANGARN = INTHR
BANGTIMER = 1

where

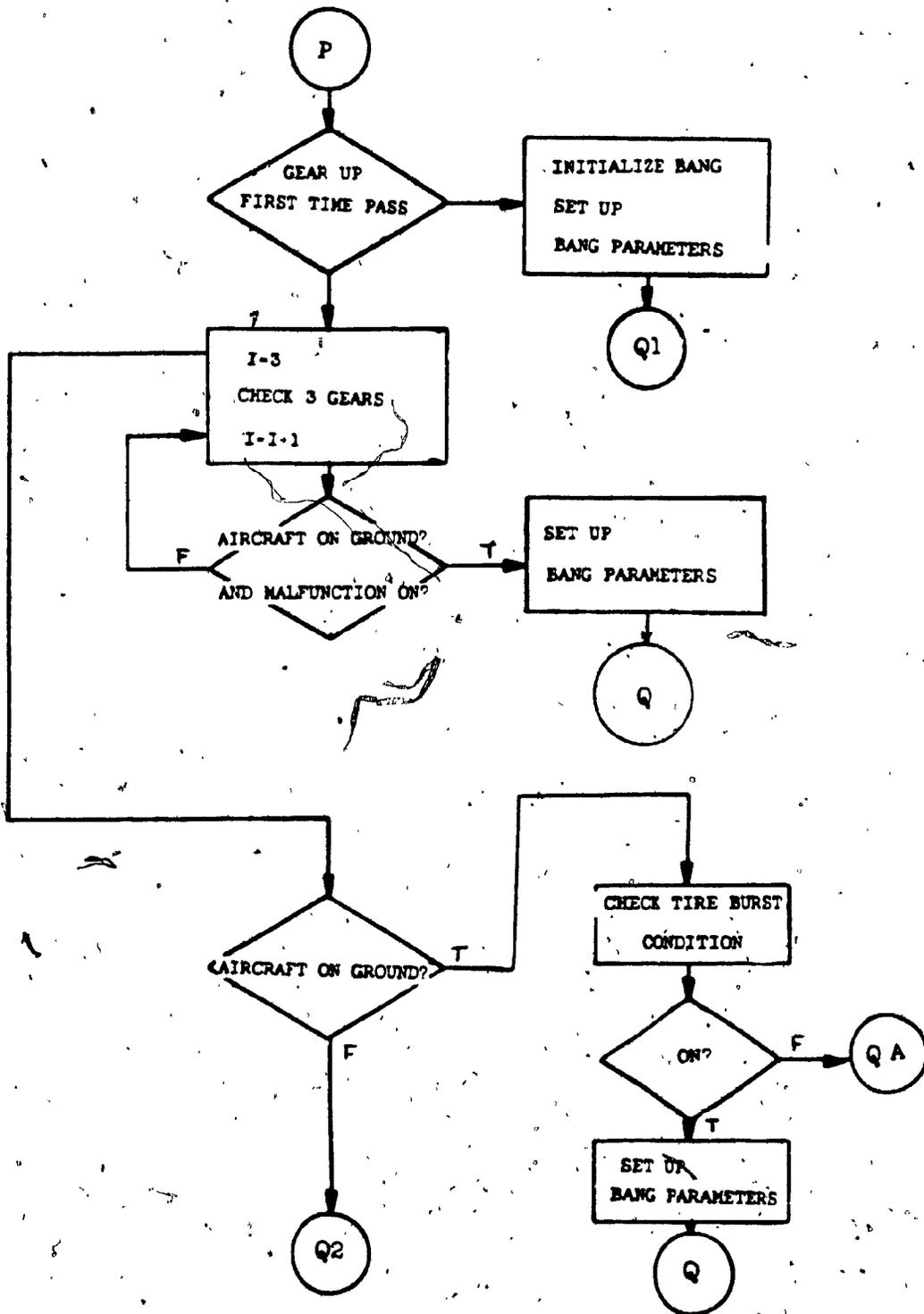
I the engine number
INTHR bang amplitude constant



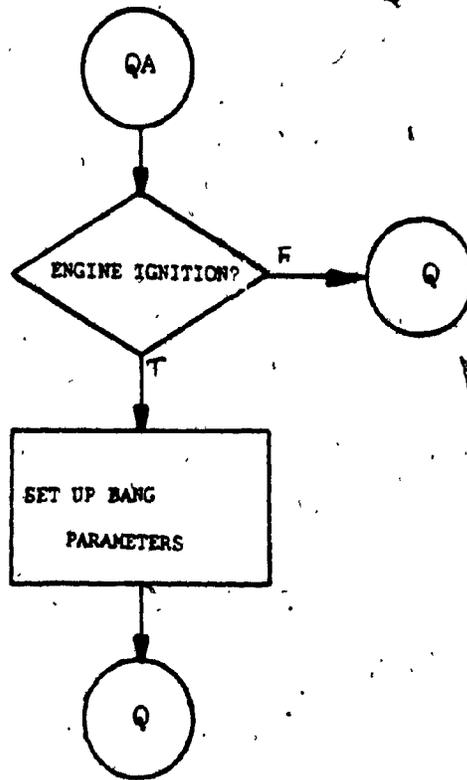
*FIGURE 5.28 Bang Sounds Program Flowchart *



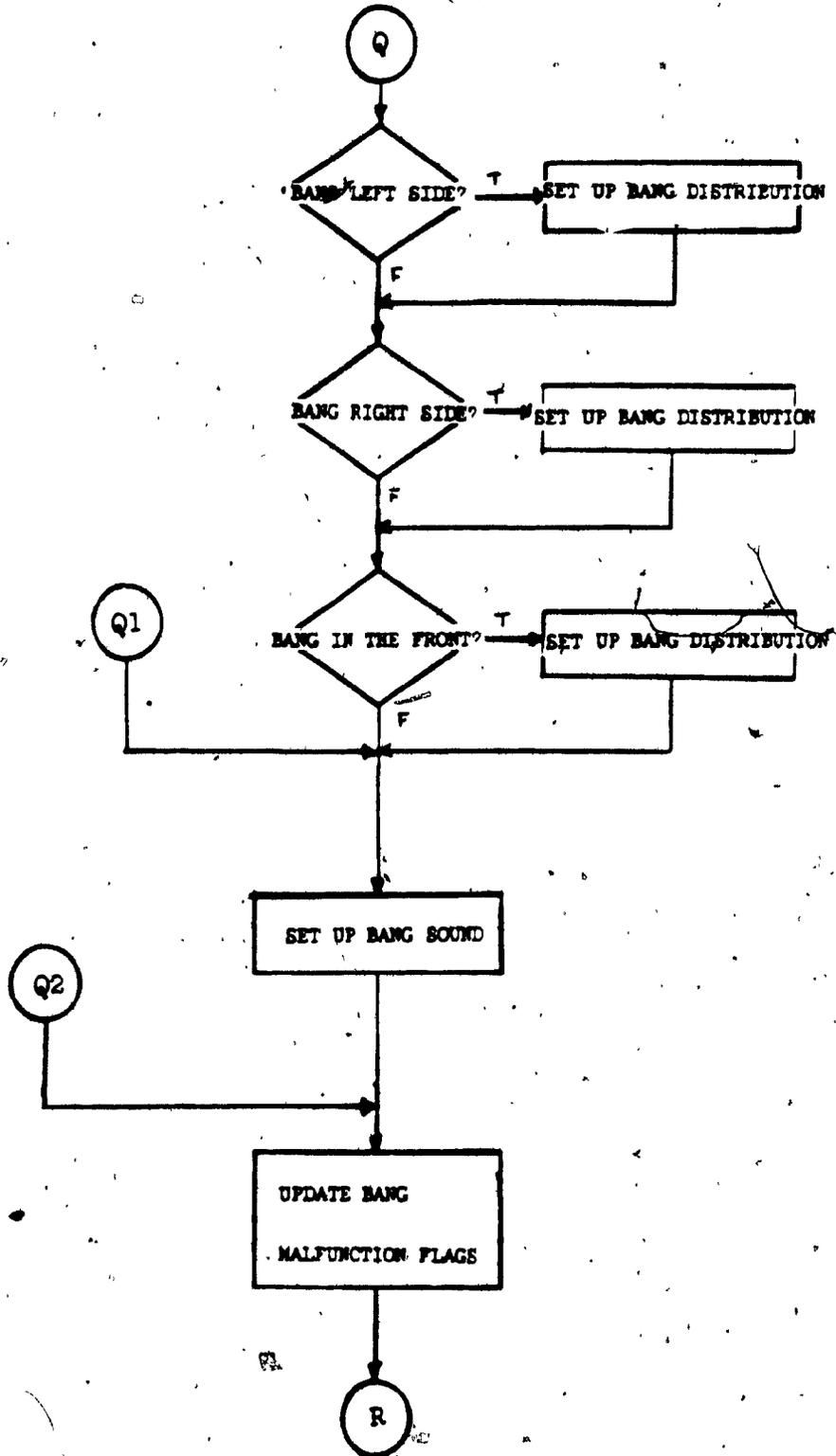
*FIGURE 5.29 Bang Sounds Program Flowchart *



*FIGURE 5.30 Bang Sounds Program Flowchart *



*FIGURE 5.31 Bang Sounds Program Flowchart *



*FIGURE 5.32 Bang Sounds Program Flowchart *

5.8 Ground Power Units

These two units are external to the aircraft, and they are a part of the aircraft's preparation for take off. The electrical power unit fulfills the electrical power demands to turn the aircraft systems on. The pneumatic unit supplies the appropriate air pressure to ignite the engines. This section computes the sounds generated by these units.

5.8.1 System Description -

The electric power unit sound is simulated using a repetitive waveform and it is turned on by the instructor, through the instructor facilities module

The pneumatic unit is produced following the same process, and is also a function of the engine pneumatic demands during ignition on, and ignition cutout.

5.8.2 Program Description -

a. Electric Unit

The sound, as all repetitive sounds, is pre-programmed and is saved into a table. Instead of turning the sound on directly, its amplitude is slewed up slowly as shown in equation 30. Its amplitude and frequency are set through the following equations respectively :

$$\text{CONTINO4}(4) = (\text{EGPAMP} - \text{CONTINO4}(4)) * \text{EGUP} + \text{CONTINO4}(4)$$

equation 30

$$\text{CONTINO4}(1) = \text{EGPUF}(1)$$

equation 31

where

EGPAMP fixed amplitude for GPU, constant
 EGUP tuning constant for sound level
 EGPUF fixed frequency constant

b. Pneumatic Unit

The amplitude and frequency computations are as follows:

$$\text{CONTINO5}(4) = \text{MIN}(\text{INITAM} * \text{EXP}(Y) , 255.)$$

equation 32

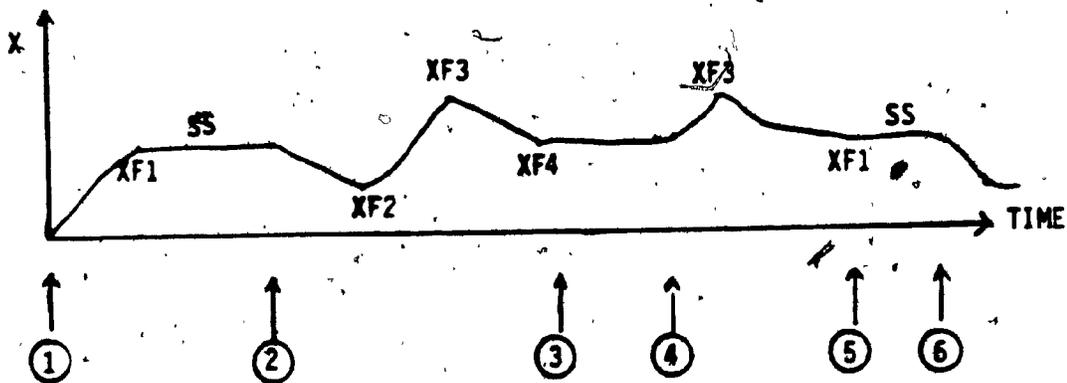
$$\text{CONTINO5}(1) = \text{MIN}(\text{INITFR} * \text{EXP}(X) , 255.)$$

equation 33

where

INITAM initial amplitude constant
 Y a function described in figure 5.33
 INITFR initial frequency constant
 X a function described in figure 5.34

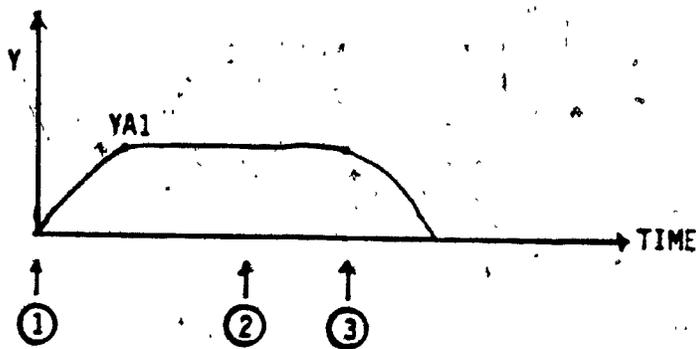
The discrete frequency components which are stored in the tables are shown in figures 5.35, 5.36, whereas the flowcharts are presented in figures 5.37, and 5.38.



For Frequency

- ① Pneumatic GPU start switch (instructor)
- ② Engine ignition ON
- ③ Steady state
- ④ Engine ignition cutout
- ⑤ Steady state
- ⑥ Pneumatic GPU OFF
- SS Steady state

FIGURE 5.33 X-function



- ① GPU start
- ② Steady state
- ③ GPU OFF

FIGURE 5.34 Y-function

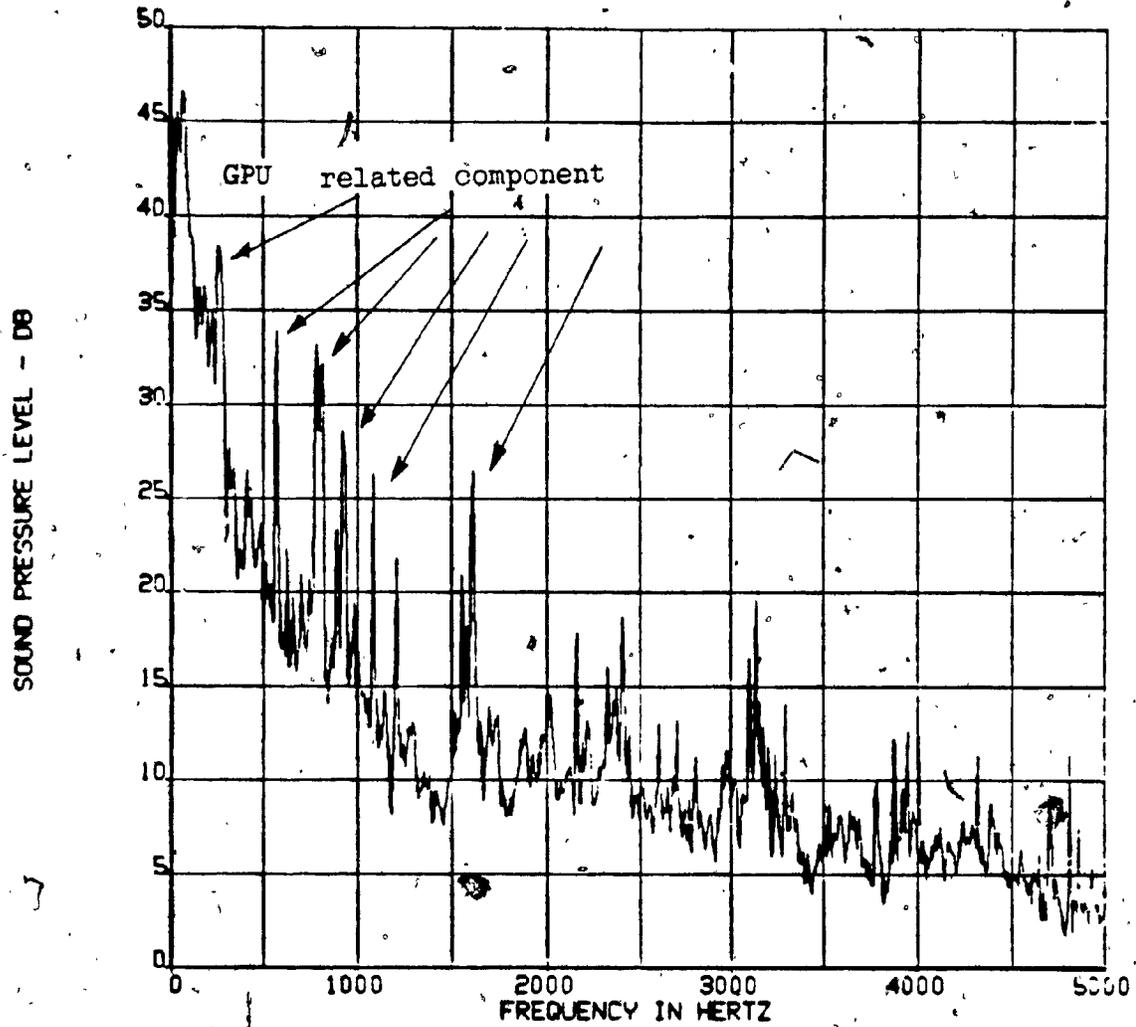
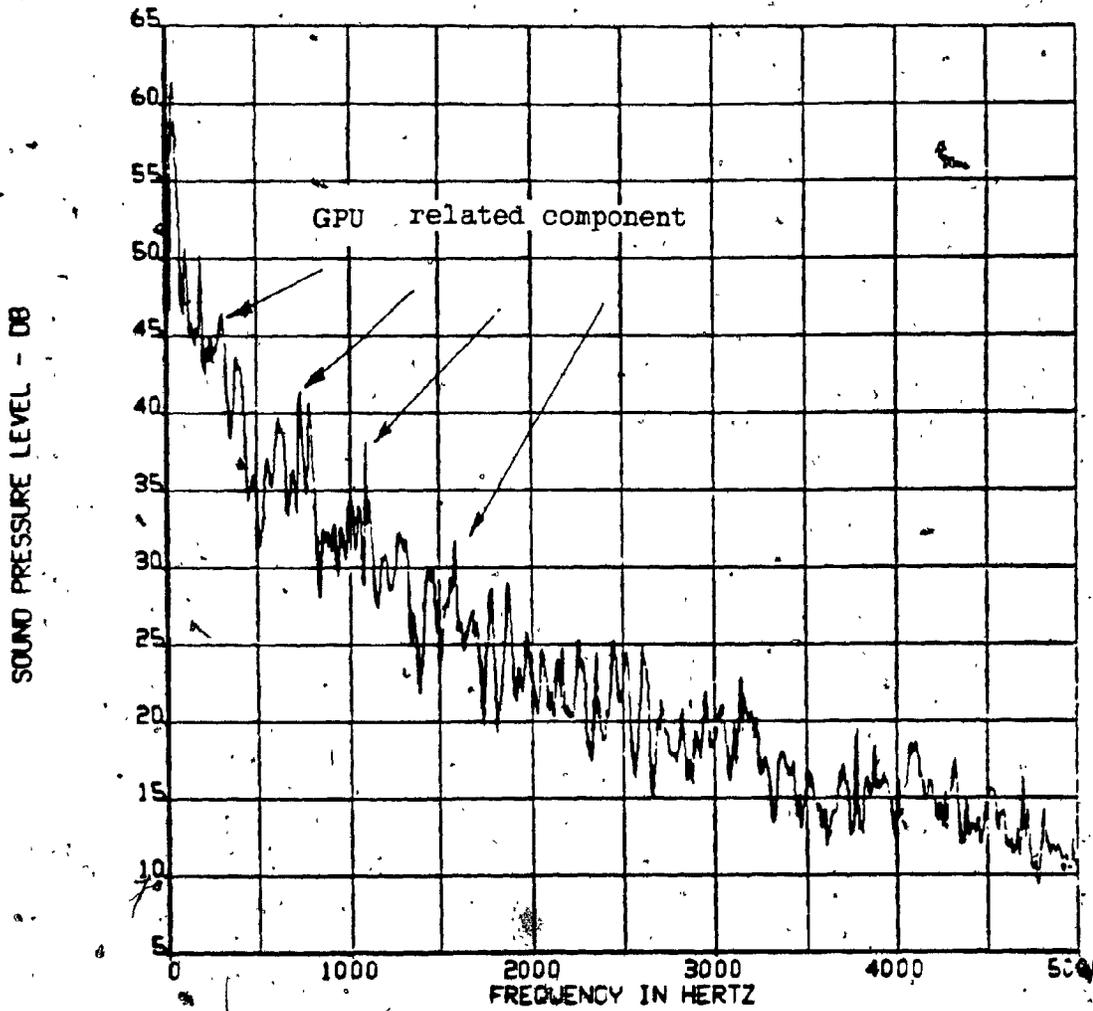
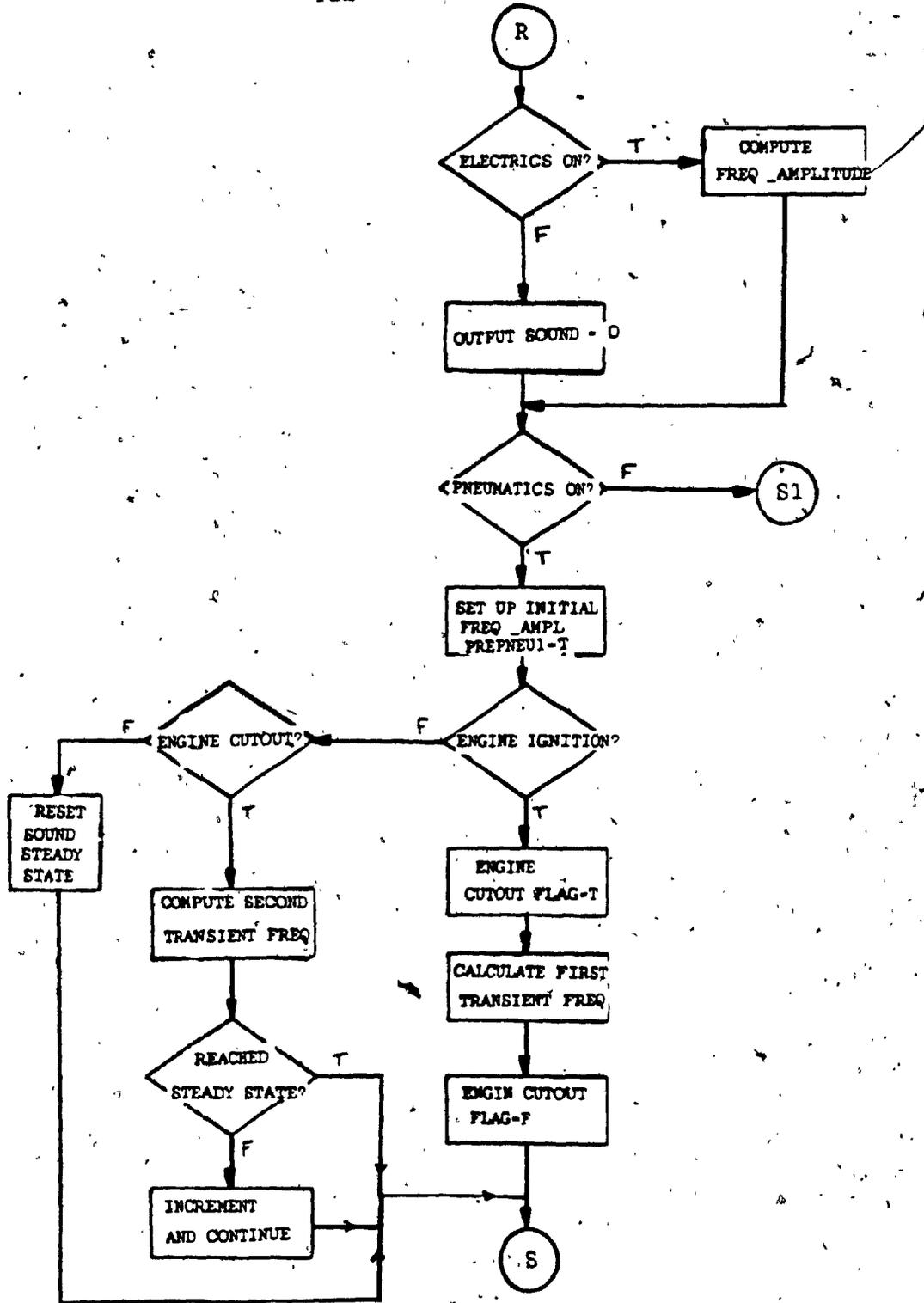


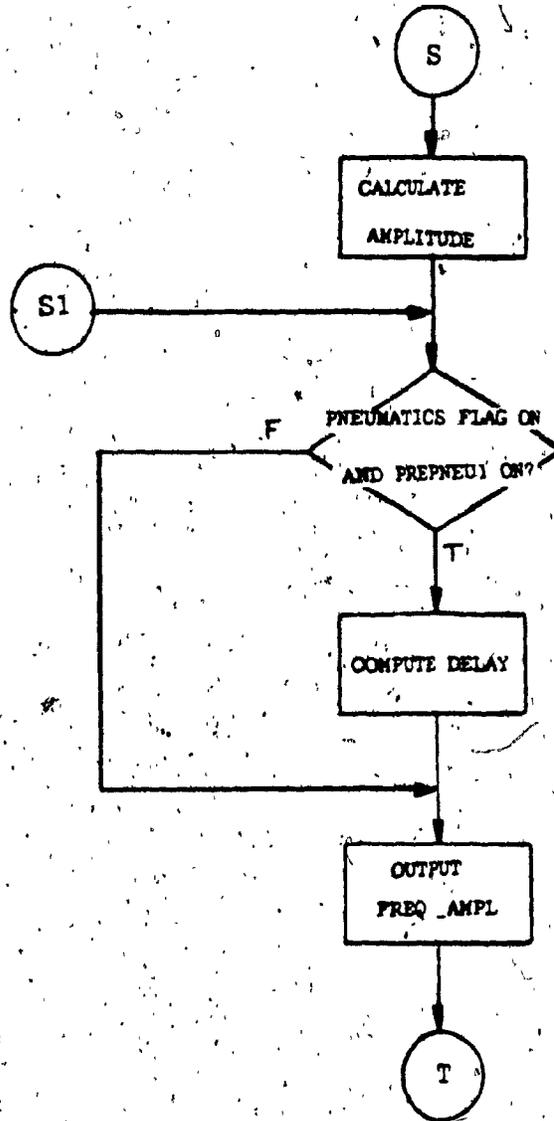
FIGURE 5.35 External Electrics



*FIGURE 5.36 External Pneumatics *



*FIGURE 5.37 GPU Program Program Flowchart *



*FIGURE 5.38 GPU Program Flowchart *

5.9 Hydraulic Pumps

The Hydraulic pumps are located at the rear of the aircraft and they generate a high pitched whine, very low in amplitude.

5.9.1 System Description -

The sound is produced using the high frequency oscillators. Depending on the type of aircraft, this sound, in some cases, might not be audible at all. In figure 5.39 we can see main frequency component of the hydraulic pumps sound.

5.9.2 Program Description -

Amplitude and frequency are set through the following equations :

$$VCOA05 = HYPAMP \quad \text{equation 34}$$

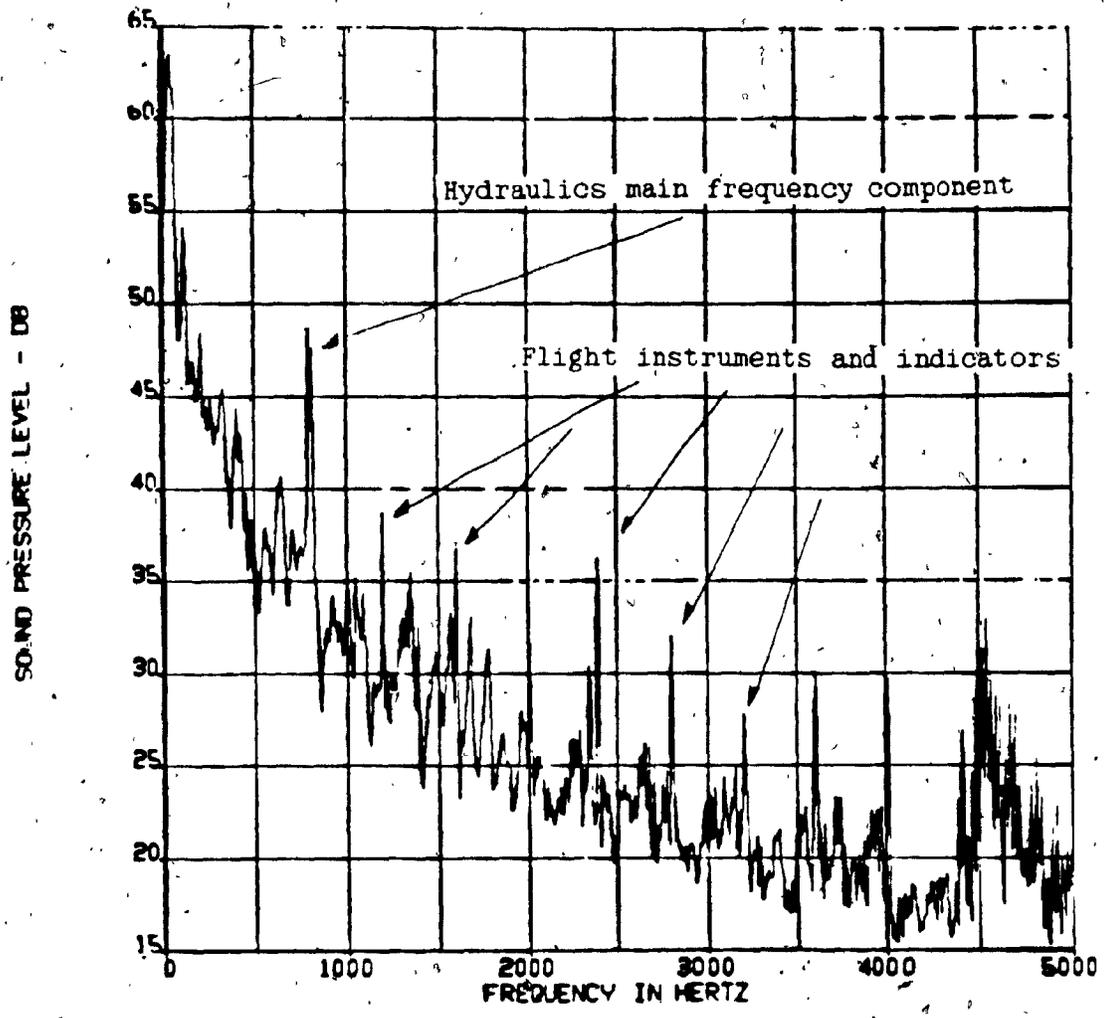
$$VCOF05 = HUPFRE \quad \text{equation 35}$$

where

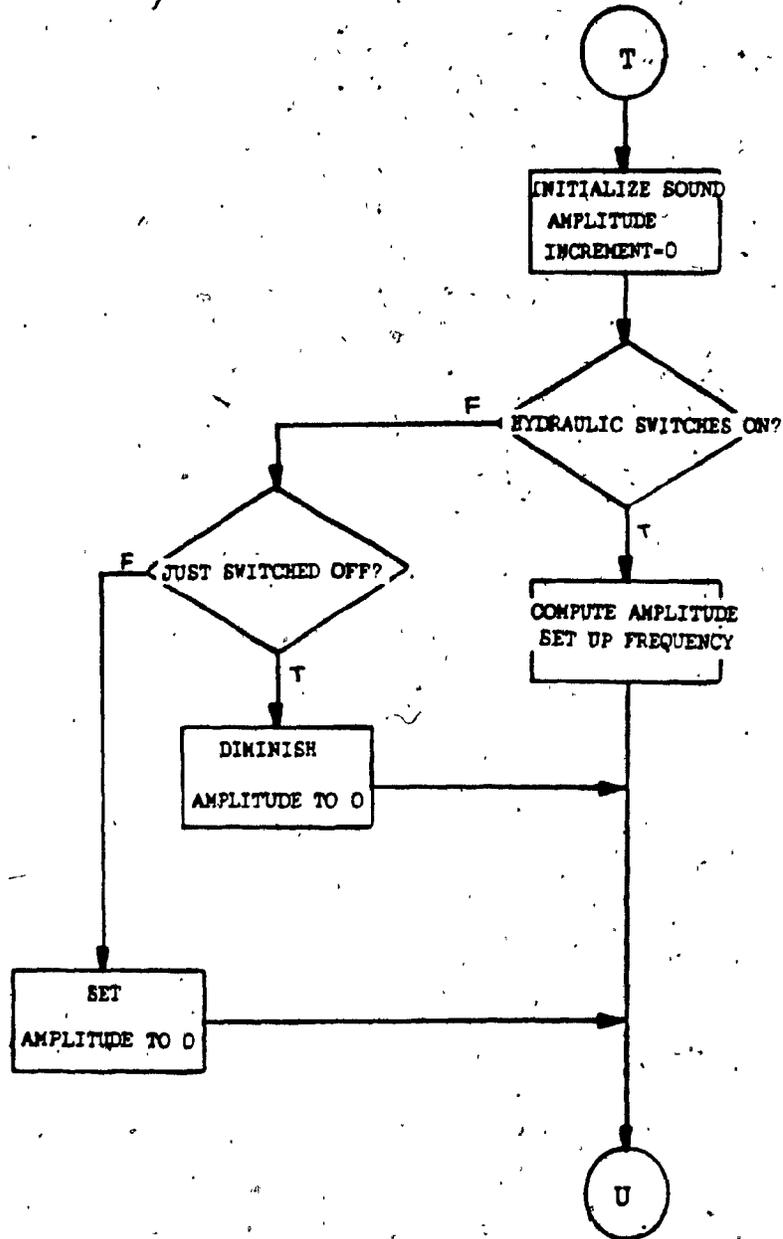
HYPAMP amplitude tuning constant

HUPFRE frequency tuning constant

The flowchart is presented in figure 5.40



*FIGURE 5.39 Hydraulic Pumps *



*FIGURE 5.40 Hydraulics Program Flowchart *

5.10 Rain And Hail

This part of the program simulates rain and hail conditions as heard in the cockpit.

5.10.1 System Description -

Rain and hail are two examples of random noise. They can be selected through the instructor facilities and controls.

5.10.2 - Program Description -

Five (5) white noise generators are used, and the output is a function of speed and wind gust. The equations for the effects are given below. The flowchart is presented in figure 5.41.

a. Noise

$$\text{RAINL} = \text{MAX}(\text{MIN}(\text{VELOCITY} * \text{RAND1} * \text{SLEWAMP}, 32767), 0.)$$

equation 36

$$\text{RAINR} = \text{RAINL}$$

equation 37

$$\text{WNAMP}(6) = \text{MIN}(\text{RAINL} + \text{AEROL} + \text{RAPDEC1} + \text{AIRCON}, 32767.0)$$

$$\text{WNAMP}(8) = \text{MIN}(\text{RAINR} + \text{AEROR} + \text{RAPDEC2} + \text{AIRCON}, 32767.0)$$

where

RAINL temporary variable

RAINR temporary variable

SLEWAMP rain amplitude constant

VELOCITY equivalent wind velocity variable

RAND1 equivalent random gusts variable

AEROL, AEROR, AIRCON, RAPDEC1, RAPDEC2, are compensations to the white noise generators from the calculations for aerohiss and air-conditioning and rapid decompression (equations 15, 16, 17, 18, 19)

b. Bursts -

$$WNAMP(5) = \text{MAX}(\text{MIN}(\text{VELOCITY} * \text{RAND2} * \text{SLEWAMP} .32767.), 0.)$$

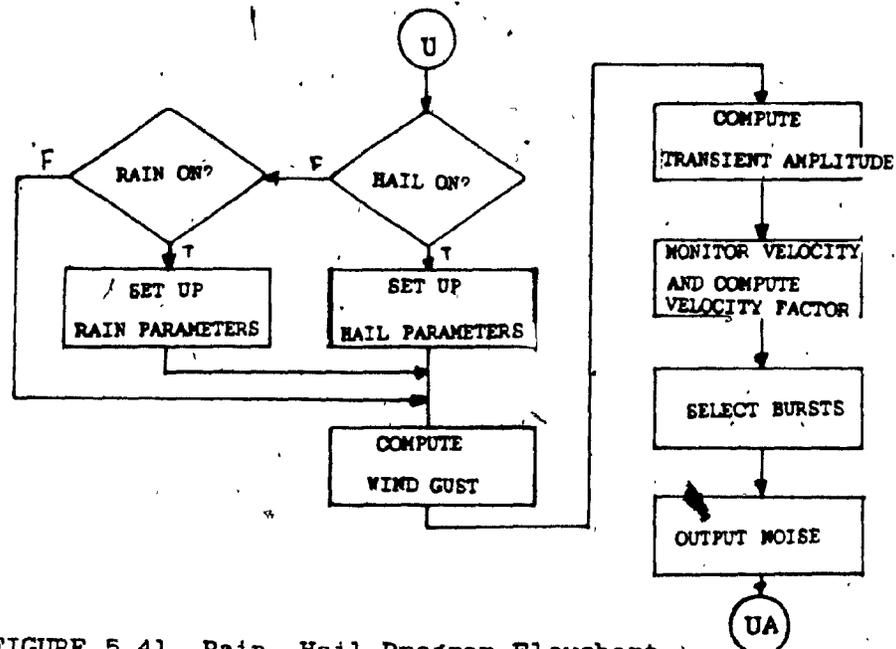
equation 38

$$WNAMP(7) = WNAMP(1) = WNAMP(5)$$

where

RAND2 equivalent random gusts variable

To differentiate between rain and hail, since the equations for both effects are similar, a different burst rate and randomness of gusts are selected.



*FIGURE 5,41 Rain_Hail Program Flowchart

5.11 Crash And Scrape

This sound is generated in any general crash condition, or it can be evoked by the instructor. The Scrape condition is entered when one of the landing gears crashes while the aircraft is taxiing on the runway.

5.11.1 System Description -

The sound is computed as a random waveform and its amplitude is a function of speed.

5.11.2 Program Description -

Random generators RANDOM10, and RANDOM11 are used as follows :

$$\text{RANDOM10}(1) = \text{MIN}(\text{VVE} * \text{CRSCNT}, 255.) \quad \text{equation 39}$$

$$\text{RANDOM11}(1) = \text{MIN}(\text{VUG} * \text{CRSCNT}, 255.) \quad \text{equation 40}$$

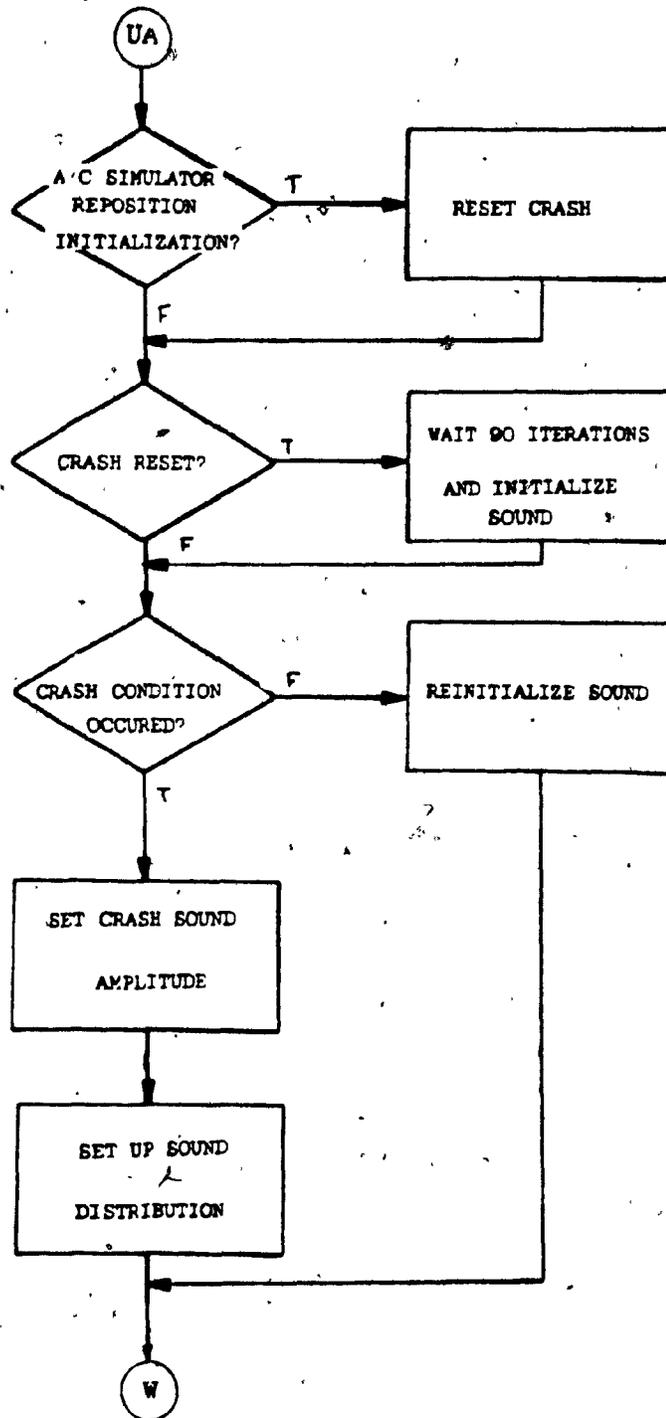
where

VVE equivalent air speed variable

VUG speed with respect to ground variable

CRSCNT tuning constant

Figure 5.42 presents the flowchart for the programming.



*FIGURE 5.42 Crash_Scrape Program Flowchart *

5.11.3 Thunder Effect -

The effect is turned on by the instructor facilities at will and except the sound effect that is generated in the cockpit, it also produces a disturbance in the communication system (static discharge interference).

5.11.4 System Description -

The thunder sound is a low frequency rumble sound with echo-like quality.

5.11.5 Program Description -

One repetitive and random waveform is used. The distribution of the sound is variable from the front to the back speakers. The equations used for the computation are as follows :

$$J=J+1$$

$$\text{CONTIN11}(4) = \text{THUNDER} * \text{LIGHTTIMER} \cdot (J^2) \quad \text{equation 41}$$

$$\text{RANDOM03}(1) = \text{CONTIN11}(4) \quad \text{equation 42}$$

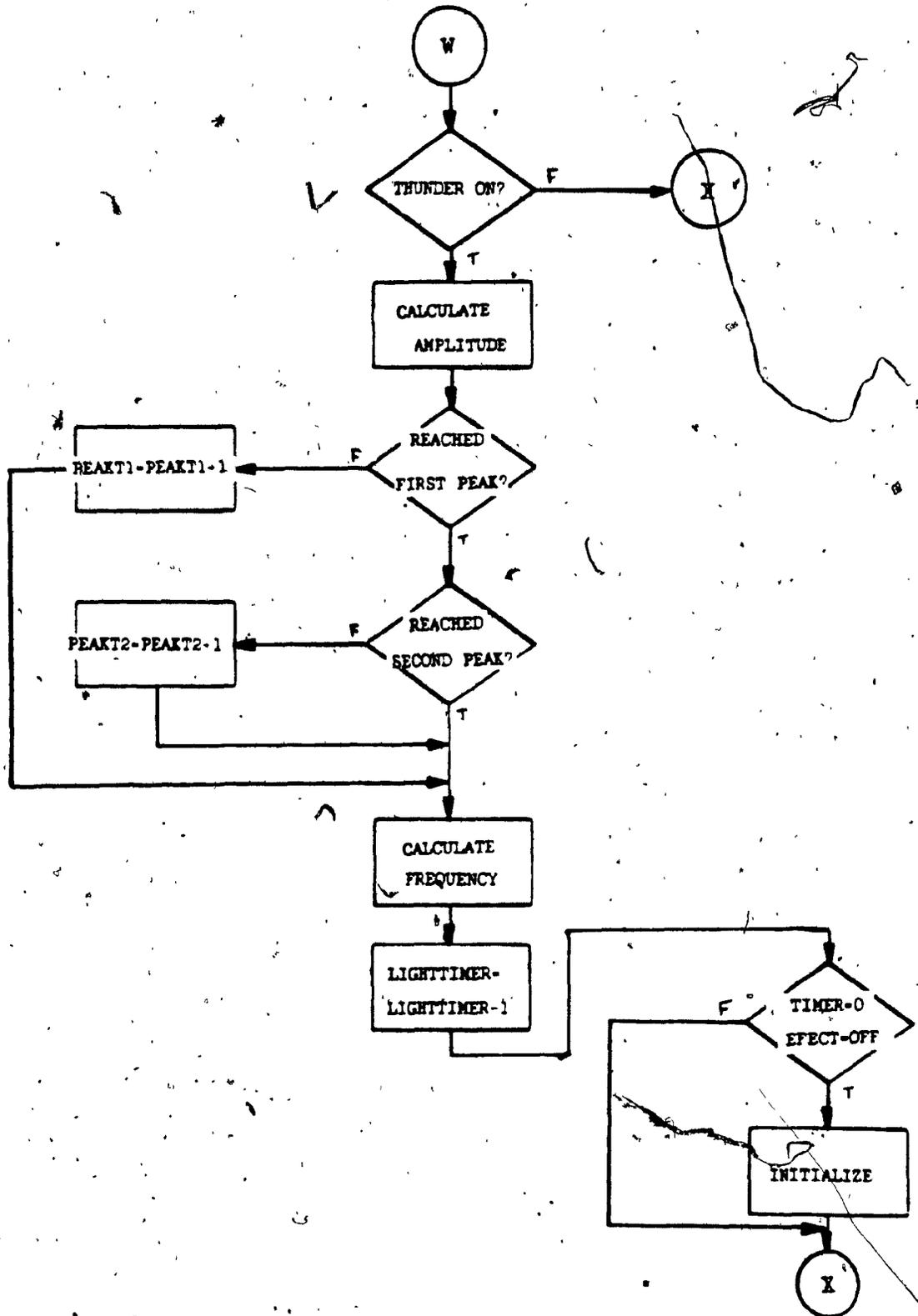
where

J counter used to create amplitude peaks

THUNDER tuning constant

LIGHTTIMER sound duration constant

The flowchart is given in figure 5.43 .



*FIGURE 5.43 Thunder Program Flowchart *

5.12 Volume Control

The total volume of the simulated sound is set in this section.

5.12.1 System Description -

The volume of the six channels is preset according to a specified value. A button also permits muting of the sound if desired.

5.12.2 Program Description -

The labels of the six channels are as follows :

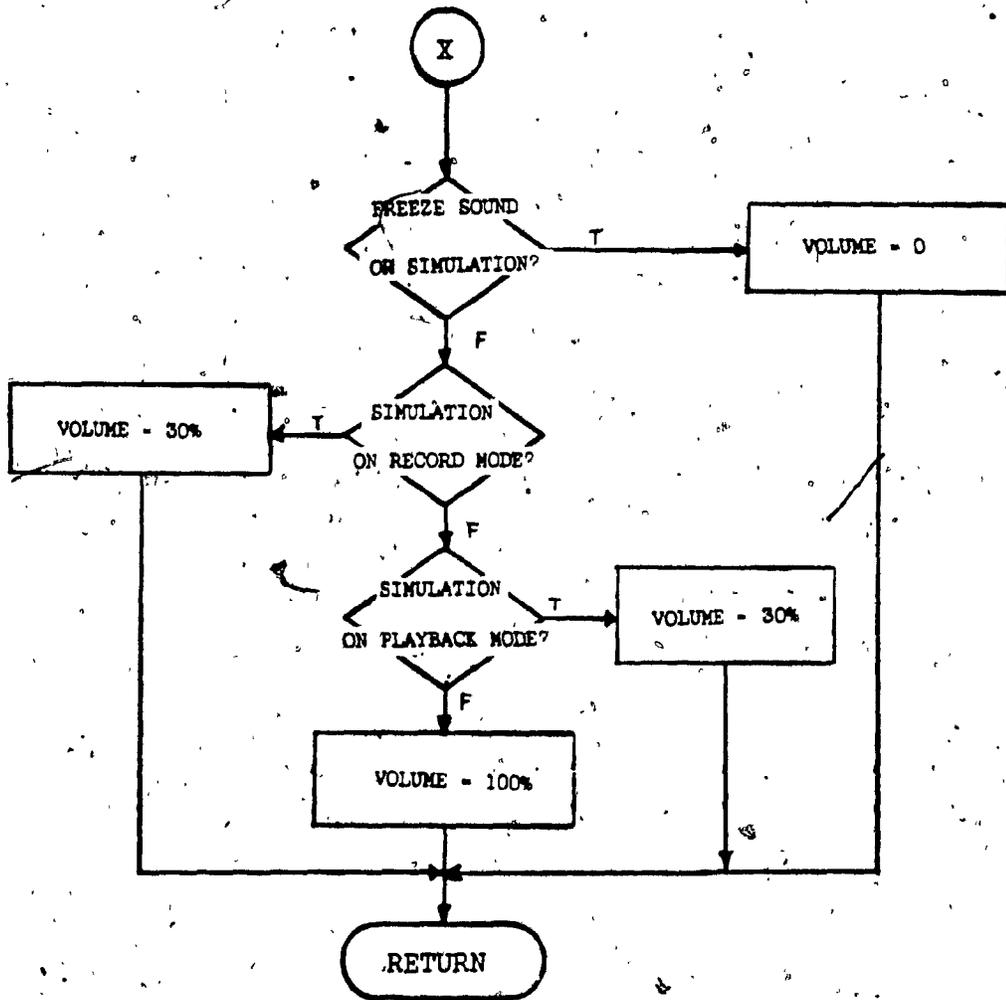
VOLUME(I) = TOTVOLⁿ in normal operation

VOLUME = 0 if sound.mute is ON

where

TOTVOL tuning constant

The flowchart is given in figure 5.44 .



*FIGURE 5.44 Volume Program Flowchart *

CONCLUSION

A sound simulation system was examined in all its phases: Sound data acquisition, data analysis and the effects of ambient noise, a hardware system conception and realization, along with the software background for sound generation. Finally the sound module was examined in depth.

As a result a sound system was implemented and it was able to match the reference data, and the simulation requirements in most cases. A very important factor in the whole simulation method was the fine tuning session with the evaluation training pilots on the simulator itself. Problems of relative sound amplitudes for different systems, were solved in that session.

The limitation that the system faced, was the small amount of harmonic components it provided for various sounds, and in particular in the engines' sound simulation.

The system as a whole, when compared to a completely digital sound generation system, makes certain compromises as far as total digital control is concerned, or point by point simulation. But it combines the advantages of both methods by imposing less requirements on the dedicated sound microprocessor.

LIST OF REFERENCES

- [1]. R.B. Randall : "Frequency Analysis"
Bruel Kjaer, Denmark 1979
- [2]. Hal Chamberlin :
"Musical Applications of Microprocessors"
Hayden Book Company, Inc., Rochelle Park, New Jersey, 1980
- [3]. CAE Electronics : "Simulation Specifications"
Reference document no. TPD 8069 , 1980
Montreal, Canada
- [4]. J. Langlois : "DUSK Microprocessor system"
CAE Electronics, 1980
Montreal, Canada
- [5]. A. Antoniadis : "Olympic Airways Sound model report"
Reference document no. 97515 03 J326, 1980
CAE, Montreal, Canada
- [6]. Boeing Commercial Airplane Co. : "737-200 Sound Tapes"
Seattle Washington, 1980
- [7]. Boeing Commercial Airplane Co.
"Crew Training Simulator Flight Deck Sound Data"
Reference document no. D6-38026
Seattle Washington, 1980
- [8]. Boeing Commercial Airplane Co. : "Auxilliary Power Unit"
Operations Manual.
Seattle Washington, 1980

- [9]. Boeing Commercial Airplane Co.: "737-200 Engine data"
Operations Manual.
Seattle Washington, 1980
- [10]. Boeing Commercial Airplane Co.:
"737-200 Air-conditioning"
Operations Manual.
Seattle Washington, 1980
- [11]. Boeing Commercial Airplane Co.:
"737-200 High Lift Devices"
Operations Manual.
Seattle Washington, 1980
- [12]. Boeing Commercial Airplane Co.: "737-200 Landing Gear "
Operations Manual:
Seattle Washington, 1980
- [13] Simon Haykin : "Communication Systems"
John Wiley Sons 1978
New York
- [14]. J.R. Hassall, K.Zaveri: "Acoustic Noise Measurements"
Bruel Kjaer, Denmark 1979
- [15]. CAE Electronics : "Sound System Proposal"
Reference document id. MSP. 1985.
Montreal, Canada

APPENDIX A
LIST OF VARIABLES

-- ENGINES --

Internal constants

| | | |
|-----------|-------------------------------|------|
| ITERCNT | constant for interpolation | REAL |
| ITERNO | constant for interpolation | REAL |
| ITEREC | constant for interpolation | REAL |
| INN1P | N1 RPM function for interp. | REAL |
| INN2P | N2 RPM function for interp. | REAL |
| DELN1P | N1 RPM function for interp. | REAL |
| DELN2P | N2 RPM function for interp. | REAL |
| RSP1 | scratch pads | REAL |
| RSP2 | scratch pads | REAL |
| ALTIDU | tuning constant | REAL |
| OLTITU | parameter, altitude | REAL |
| SPEED | tuning constant, speed | REAL |
| SPODE | parameter, speed | REAL |
| AMPLFN | amplitude factor for engines | REAL |
| PREFFL(2) | previous value of flame flag | BYTE |
| SNDWFS(2) | sound amplitude thrust | REAL |
| INTHR | initial thrust amplitude | REAL |
| FORTHR | forward thrust level | REAL |
| REVTNR | reverse thrust level | REAL |
| AM2(2) | N2 function for ampl. calc. | REAL |
| AM(2) | N1 function for ampl. calc. | REAL |
| KC | param. for high freq. scaling | REAL |
| KT | sampling rate | REAL |

| | | |
|-----------|-----------------------------------|-------|
| ENGWHITE | const. for eng. white noise | REAL |
| HIAMP | const. for high freq. amplit. | REAL |
| LOWAMP | const. for low freq. amplit. | REAL |
| RANDOM01A | Array of elements for ampl.random | BYTE |
| RANDOM01F | Array of elements for freq.random | BYTE |
| CONTINO1A | Array of elements for ampl.repet. | INT*2 |
| CONTINO1F | Array of elements for freq.repet. | INT*2 |
| WNAMP | Array of elements for white noise | INT*2 |

Input variables

| | | |
|----------|---------------------------|-------|
| EFW(2) | fuel flow | REAL |
| EN1(2) | N1 % RPM | REAL |
| EN2(2) | N2 % RPM | REAL |
| EFFL(2) | engine flame flags | LOG*1 |
| EDREV(2) | reverse door pos'n 1=open | REAL |
| VHH | pressure altitude - feet | REAL |
| VVE | equivalent airspeed | REAL |

Output variables (INT*2)

| | | |
|----------|-------------------------------|--------|
| CONTINO1 | engine 1 output table | |
| CONTINO2 | engine 2 output table | |
| RANDOM01 | engine 1 thrust noise | |
| RANDOM02 | engine 2 thrust noise | |
| VCOA02 | engine 1 amplitude high freq. | chan 1 |
| VCOA03 | engine 2 amplitude high freq. | chan 2 |
| VCOF02 | engine 1 frequency high freq. | chan 1 |

| | | |
|---------|-------------------------------|--------|
| VCOF03 | engine 2 frequency high freq. | chan 2 |
| NOISE02 | engine 1 white noise | chan 1 |
| NOISE03 | engine 2 white noise | chan 2 |

-- APU --

Internal

| | | |
|---------|-------------------------------|------|
| APUAMP1 | amplitude tuning constant | REAL |
| APUAMP2 | amplitude tuning constant | REAL |
| FREQ | frequency of APU | REAL |
| RPM | calibration constant | REAL |
| KC | high frequency scaling factor | REAL |
| APUFRE | frequency tuning constant | REAL |

Inputs

| | | |
|-------|---------------------------------|------|
| AURPM | APU RPM | REAL |
| VUG | X-Velocity wrt to ground ft/sec | REAL |

Outputs

| | | |
|---------|------------------------------|-------|
| VCOA(1) | APU high frequency amplitude | INT*2 |
| VCOF(1) | APU high frequency frequency | INT*2 |

-- AEROHISS NOISES --

Internal

| | | |
|--------|------------------------|------|
| FLAPOS | average flap position | REAL |
| RSP1 | scratchpad | REAL |
| FSLOPE | flap geometry constant | REAL |

| | | |
|-----------|----------------------------------|-------|
| YFLAP | flap geometry constant | REAL |
| KFLAP | average flap position | REAL |
| RANDOM08A | aeronoise of flaps | BYTE |
| RANDOM04A | aeronoise of speed brakes | BYTE |
| SPOIL | average spoiler position cnst | REAL |
| SPOILERS | function of spoiler position | REAL |
| AEROL | left wing sideslip function | REAL |
| AEROR | right wing sideslip function | REAL |
| RSP2 | scratchpad | REAL |
| GEARHISS | tuning constant for landing gear | REAL |
| RANDOM06A | random noise for landing gear | BYTE |
| RAPDEC1 | rapid decompression noise ampl. | INT*2 |
| RAPDEC2 | rapid decompression noise ampl. | INT*2 |
| KDECOMP | tuning const. rapid decomp. | REAL |
| DECOMPF | rapid decompression flag | BYTE |
| RSP3 | scratchpad | REAL |
| GASUP | gasper fan up transient | REAL |
| GASDWN | gasper fan down transient | REAL |
| AIRAMP | air packs amplitude | REAL |
| FAN | cabin fan constant | REAL |
| DNWCC | cabin inflow | REAL |
| RANDOM05A | random noise for pack flow | BYTE |
| WNAMP(12) | amplitude white noise aerohiss | INT*2 |
| VOFFST | tuning constant offset aerohiss | REAL |
| HISLMT | const. overflow limit aerohiss | REAL |
| PRESS | constant rapid decompression | REAL |

| | | |
|-------|--------------------------|------|
| SLIP1 | tuning constant sideslip | REAL |
| SLIP2 | tuning constant sideslip | REAL |

Inputs

| | | |
|----------|---------------------------------|------|
| AWFL | average flap position - left | REAL |
| AWFR | average flap position - right | REAL |
| AWLEFL | average slat position - left | REAL |
| AWLEFR | average slat position - right | REAL |
| CSP | slat lever position - degrees | REAL |
| AGGPL(3) | gear position | REAL |
| DTPDI | cabin pressure differential | REAL |
| IDDNGFAN | gasper fan switch | |
| DTHCC | cabin altitude pressure | REAL |
| CSBGND | average ground spoiler position | REAL |
| VBETA | slip angle | REAL |

Outputs (BYTE)

| | |
|----------|---------------------------------|
| RANDOM04 | spoiler aeronoise |
| RANDOM05 | external air conditioning |
| RANDOM06 | landing gear aeronoise |
| RANDOM08 | flaps and slats aeronoise |
| NOISE08 | white noise cabin decompression |
| NOISE06 | white noise cabin decompression |
| NOISE08 | aerodynamic hiss |
| NOISE12 | aerodynamic hiss |
| NOISE06 | aerodynamic hiss |

-- WINDSHIELD WIPERS --

Internal

| | | |
|-----------|-----------------------------------|------|
| WIPON | windshield wiper flap flag | BYTE |
| WWRPM(I) | windshield wiper frequency | REAL |
| ADDR(I) | table address, different speeds | REAL |
| CONTINO6A | amplitude of repetitive sound | BYTE |
| CONTINO6F | frequency of repetitive sound | BYTE |
| PREPARK | previous w w position flag | BYTE |
| COUNT | counter for w w park return posn | BYTE |
| COUNTFLG | flag indicating status of counter | BYTE |
| YTSIMT | simulator timer | REAL |
| WWRAIN1,2 | rain effect on wipers | REAL |
| FPX | freq. and ampl. modulating factor | REAL |
| WRPM | frequency modulating factor | REAL |
| WHINEAMP | rain dependent amplitude factor | REAL |
| RAIN1 | tuning constant | REAL |
| RAIN2 | tuning constant | REAL |
| TWIPA | rain effect amplitude | REAL |
| TWIPF | rain effect frequency | REAL |

Inputs

| | | |
|------------|---------------------------|------|
| IDAMWWP(I) | windshield wiper selector | BYTE |
| BI54 | breaker left wiper | BYTE |
| BI55 | breaker right wiper | BYTE |

Outputs (INT*2)

CONTINO6 windshield wiper sound
VCOA11 high freq rain component - ampl.
VCOA11 high freq rain component - freq.
VCOA12 high freq rain component - ampl.
VCOA12 high freq rain component - freq.

--- RUNWAY RUMBLE ---

Internal

FLITE flight level flag BYTE
TSQUEAL1 tuning constant REAL
TSQUEAL2 tuning constant REAL
TSQUEAL3 tuning constant REAL

Inputs

SQUEAL squeal flag BYTE
AHPOS13 front wheel skidding factor REAL
VTHED euler wheel angle REAL
VVE airspeed equivalent REAL
VH height above ground REAL
VEE gear compression REAL

Outputs

VCOA amplitude oscillator 1 REAL
VCOF frequency oscillator 1 REAL

| | | |
|--------|------------------------|------|
| VCOA04 | amplitude oscillator 4 | REAL |
| VCOFO4 | frequency oscillator 4 | REAL |

-- BANG SOUNDS --

Internal

| | | |
|-----------|--------------------------------|-------|
| BANGTIMER | timer for bang duration | REAL |
| BANGRST | bang reset flag | BYTE |
| BANGL | left bang | BYTE |
| BANGR | right bang | BYTE |
| BANGD | bottom and front bangs | BYTE |
| BANGDIST | distribution of sound | INT*2 |
| BANGARN | random bang amplitude | REAL |
| BANGAMP | engine seize tuning ampl | REAL |
| COUNT1 | counter for decompression bang | REAL |
| DECOMPF | decompression flag | BYTE |
| CRASH | crash flag | BYTE |
| GEARCOLL | gear collapse flag | BYTE |
| AMP | turbine failure | REAL |
| LIGHTFL | light-up flag | BYTE |
| PREDECOMP | previous state decompression | BYTE |
| PREFRAIL | previous state turbine failure | BYTE |
| RANDOM09A | random amplitude bang sound | INT*2 |
| CONTINO8A | repetitive ampl. bang sound | INT*2 |
| PREBURST | previous state tire burst flag | BYTE |
| BURST | tire burst flag | BYTE |
| ENGSURGL | left engine surge flag | BYTE |

| | | |
|----------|-----------------------------|------|
| ENGSURGR | right engine surge flag | BYTE |
| CCOUNT5 | counter for surge, left | REAL |
| CCOUNT6 | counter for surge right | REAL |
| AMPSURG | surge amplitude | REAL |
| COMPSTAL | turbine failure flag | BYTE |
| CCOUNT2 | counter for turbine failure | REAL |
| GEUPLAMP | gear uplock tuning constant | REAL |
| SRGAMP | engine surge ampl. trigger | REAL |
| SURFRAC | surge ampl. tuning constant | REAL |

Inputs

| | | |
|------------|-----------------------|-------|
| TF71111 | engine seizure left | LOG*1 |
| TF71112 | engine seizure right | LOG*1 |
| TF71101 | engine surge left | LOG*1 |
| TF71102 | engine surge right | LOG*1 |
| TF71011 | turbine failure left | LOG*1 |
| TF71012 | turbine failure right | LOG*1 |
| TF21011 | decompression bang | LOG*1 |
| TCMREPOS | reposition aircraft | LOG*1 |
| VEOG | a c on ground flag | LOG*1 |
| TF32011 | gear collapse | LOG*1 |
| TF32012 | gear collapse | LOG*1 |
| TF32013 | gear collapse | LOG*1 |
| TF32091(4) | tire burst | LOG*1 |
| ACUPLCKN | gear uplock | REAL |

Outputs

| | | |
|------------------------|-------------------------------|-------|
| RANDOM09 | bang sound (random component) | INT*2 |
| CONTINO8 | bang sound (repetitive comp.) | INT*2 |
| - GROUND POWER UNITS - | | |
| EGPUAMP | fixed amplitude for GPU | REAL |
| KC | high freq scaling factor | REAL |
| EGUP | tuning const electric | REAL |
| PNEUMAMP | turbine start whine | REAL |
| EGPUF | frequency tuning, electric | REAL |
| PAMPL | pneumatic ampl. calculation | REAL |
| INCF1 | slope increment constants | REAL |
| INCF2 | '' | REAL |
| INCF3 | '' | REAL |
| INCF4 | '' | REAL |
| PFREQ | pneumatic freq. calculation | INT*2 |
| CONTINO4A | repetitive sound ampl. elec. | INT*2 |
| CONTINO4F | repetitive sound freq. elec. | INT*2 |
| CONTINO5A | repetitive sound ampl. pneu. | INT*2 |
| CONTINO5F | repetitive sound freq. pneu. | INT*2 |
| CUTOUT | engine ignition cutout flag | BYTE |
| PASF1 | program flow control flags | BYTE |
| PASF2 | '' | BYTE |
| PASF3 | '' | BYTE |
| CUTF4 | '' | BYTE |
| CUTF3 | '' | BYTE |

| | | |
|----------|----------------------------|------|
| INCA1 | slope increment constant | REAL |
| X | frequency control variable | REAL |
| Y | amplitude control variable | REAL |
| PREPNEU1 | previous status GPU | BYTE |
| INITAM | initial pneumatic ampl. | REAL |
| INITFR | initial pneumatic freq. | REAL |
| YA1 | limit for Y | REAL |
| XF1 | limit for X | REAL |
| XF2 | " | REAL |
| XF3 | " | REAL |
| XF4 | " | REAL |

Inputs (LOG*1)

| | |
|-----------|--------------------------|
| TCMELEC1 | external electric power |
| TCPNEU1 | external pneumatic power |
| IDESGRND | ignition on -1 ground |
| IDESGRND2 | ignition on -2 ground |
| IDDESB1 | fuel lever position |
| IDDESB2 | fuel lever position -2 |

Outputs (INT*2)

| | |
|----------|--------------------------|
| CONTIN04 | sound for electric unit |
| CONTIN04 | sound for pneumatic unit |

-- HYDRAULIC PUMPS --

Internal

S sound amplitude adjusting REAL
HYDFLG hydraulics ON flag BYTE

Inputs

IDS3R stand by rudder switch BYTE
IDS4R stand by rudder switch BYTE

Outputs

VCOA05 hydraulic pumps amplitude INT*2
VCOF05 hydraulic pumps frequency INT*2
CONTIN12 continuous wave. amp. + freq. INT*2

-- RAIN_HAIL --

Internal

WNFSEL(*) cutoff frequency select LOG*2
WNBURST(*) burst rate select LOG*2
RAINHAIL tuning constant REAL
RANEFFECT tuning constant REAL
GUSTCOUNT timer for gust REAL
GUST wind effect REAL
SLEWAMP initial and final transients REAL
RAND(*) variation in sound REAL
VELOCITY function of a c velocity REAL

| | | |
|----------|---------------------------|-------|
| WNAMP() | white noise outputs | INT*2 |
| BURSRATE | burst rate | INT*2 |
| RAINL | for amplitude calculation | INT*2 |
| RAINR | for amplitude calculation | INT*2 |

Inputs

| | | |
|---------|----------------------|-------|
| TCMRAIN | rain select | LOG*1 |
| TCMHAIL | hail select | LOG*1 |
| VVE | equivalent air speed | REAL |
| YRANDNO | random number | REAL |
| YITIM | simulator timer | REAL |

Outputs (INT*2)

| | | |
|---------|---------------------|--|
| NOISE05 | white noise outputs | |
| NOISE03 | | |
| NOISE07 | | |
| NOISE11 | | |

-- CRASH SCRAPE --

Internal

| | | |
|----------|-----------------------------|-------|
| CRASHRST | crash reset flag | REAL |
| COUNT4 | counter to initialize crash | REAL |
| GEARCOL | gear collapse flag | BYTE |
| DIST | sound distribution | INT*1 |
| CRASH | crash flag | BYTE |
| RANDOM10 | amplitude for crash sound | INT*2 |

| | | |
|----------|---------------------------|-------|
| RANDOM11 | amplitude for crash sound | INT*2 |
| CRSCNT | crash amplitude tuning. | REAL |

Inputs

| | | |
|-----------|----------------------------|------|
| TCMACGND | aircraft to ground flag | BYTE |
| TCMREPOS | reposition aircraft | BYTE |
| TCRGCOND | general aircraft condition | BYTE |
| VUG | equivalent ground speed | REAL |
| VEE(3) | gear compression | REAL |
| VH | height above ground | REAL |
| VBOG | on ground flag | BYTE |
| AGSCRL(3) | gear down flag | BYTE |

Outputs

| | | |
|----------|--------------|-------|
| RANDOM10 | random sound | INT*2 |
| RANDOM11 | random sound | INT*2 |

-- THUNDER EFFECT --

Internal

| | | |
|------------|--------------------------|-------|
| PEAKT1 | amplitude peak | INT*2 |
| PEAKT2 | amplitude peak | INT*2 |
| SWITCH1 | flag | BYTE |
| SWITCH2 | flag | BYTE |
| LIGHTTIMER | duration of sound | REAL |
| LIGHTDIST | distribution of sound | REAL |
| PRELIGHT | previous value of effect | BYTE |

| | | |
|-----------|------------------|-------|
| RANDOM03A | output amplitude | INT*2 |
| RANDOM03F | output frequency | INT*2 |
| CONTIN11A | output amplitude | INT*2 |

Inputs

| | | |
|---------|---------------------|------|
| TCMLTNG | thunder effect flag | BYTE |
|---------|---------------------|------|

Outputs

| | | |
|----------|--------------------------|-------|
| CONTIN11 | continuous thunder sound | INT*2 |
| RANDOM03 | random thunder sound | INT*2 |

-- VOLUME CONTROL --

Inputs

| | | |
|----------|----------------------------|-------|
| TCMSOUND | sound mute flag | LOG*1 |
| TRCLBT | byte control word-playback | BYTE |

Outputs

| | | |
|-----------|------------------------|-------|
| VOLUME(I) | output to six channels | INT*2 |
|-----------|------------------------|-------|

APPENDIX B
INSTRUMENTATION

HP ANALYSER TECHNICAL SPECIFICATION

FREQUENCY AND TIME CHARACTERISTICS

Frequency Domain

Modes

- Passband:** Bandwidth (BW) about center frequency (CF)
- Center Frequency (CF):** 0.016 Hz to 25 kHz, nominal
- CF Setability:** Within 1.6 Hz of desired value, typically 0.016 Hz below 250 Hz
- Bandwidths (BW):** 16 selections from 0.0 Hz to 25 kHz for CF of 25 kHz and below
- Additional 16 selections** from 0.008 Hz to 250 Hz for CF of 250 Hz and below
- Range:** $\Delta f \leq CF \pm BW/2 \leq 25 \text{ kHz}$
- Baseband:** Δf to bandwidth: BW
- CF Specifying:** 0 CF selects baseband mode
- BW:** Same as for passband mode
- Range:** Same as bandwidth

Resolution (Δf): Automatically computed from bandwidth selection
Range: 16 μ Hz to 300 Hz

Time Domain

- Time Record Lengths (T):** 32 selections from 0.005 seconds to 32.000 seconds nominal
- Resolution (Δt):** Automatically computed from T
Range: 10 μ seconds to 64 seconds

MEASUREMENT CHARACTERISTICS

Measurements Performed

- Time Domain:** View Input Channel 1 and Channel 2 Time Average Auto Correlation Cross Correlation Impulse Response Impulse Response is available as part of the transfer function measurement
- Frequency Domain:** Linear Spectrum Auto Power Spectrum Power Spectral Density or Energy Density Cross Power Spectrum Power Spectral Density or Energy Density High Resolution Auto Spectrum Transfer Function Coherence
- Histogram:** Probability Density Function

NOTE

- Passband mode does not operate for time record linear spectrum or histogram measurements
- Averaging Types:** All averaging types provide continuously calibrated results and may be paused resumed or cleared by the operator at any point in the measurement
- Stable:** Equal weighting stops after reaching selected number of averages
- Exponential:** Stable up to number of averages selected then exponential with decay constant equal to number of averages selected
- Peak Channel Hold:** Holds max value in each channel (Auto Spectrum only)
- Peak Level Hold:** Holds spectrum corresponding to maximum value of cumulative channels (Auto Spectrum only)
- Number of Averages:** From 1 to 30 000 ensemble averages

Signal Types

- Sinusoidal:** Optimizes peak amplitude accuracy
- Random:** Normalizes power to 1 Hz noise bandwidth
- Transient:** Normalizes energy to 1 Hz noise bandwidth for transient analysis
- Impact:** Same as transient but allows preview of input signals before analysis

Calibration: All measurements are fully calibrated including provision for a user entered calibration factor (K = C1/C2 for each channel (K1,K2) to give results in engineering units

| MEASUREMENT | SIGNAL TYPE | | |
|-------------------|-------------------------|-----------------------------|--------------------------|
| | Sinusoidal | Random | Transient |
| Auto Spectrum | K Vrms ² | K Vrms ² /Hz | K V ² /Hz |
| Cross Spectrum | K1 K2 Vrms ² | K1 K2 Vrms ² /Hz | K1 K2 V ² /Hz |
| Transfer Function | K2/K1 | | |
| Coherence | Unit-Less | | |
| Linear Spectrum | K Vrms | | |
| Time Record | K V | | |
| Auto Correlation | K V ² | | |
| Cross Correlation | K1 K2 V ² | | |
| Histogram | -K Range to -K Range | | |

INPUT CHARACTERISTICS

- Input Channels:** Two — via BNC connectors
- Input Impedance:**
 - Front-Panel Input: 1 M Ω shunted by <50 pF
 - Rear-Panel Input: 1 M Ω shunted by <200 pF
- Input Coupling:**
 - Single Ended: dc or ac on each channel separately, ac down 3 dB at 3 Hz nominal
 - Floating: Differential input, dc only
- Common Mode Rejection Ratio:** ≥ 65 dB below 120 Hz for differential floating input
- Maximum Common Mode Voltage:** ± 10 volts
- Full-Scale Ranges:** $\pm 0.1, 0.25, 0.5, 1, 2.5, 5$ and 10 volts peak
- Amplitude Flatness:** ± 0.1 dB over the entire frequency range ± 0.05 dB typical
- Channel-to-Channel Match:**
 - Amplitude: ± 0.1 dB, 0.05 dB typical
 - Phase: ± 5 degrees, ± 2 degrees typical
- Trigger Modes:**
 - Free Run with overlap processing: Internal on either input signal External ac or dc $\pm 5\%$ max level
 - Slope: + or -
 - Level: Adjustable from 10% to 90% of full scale
 - Delay: Independent delays on each channel either pre or post trigger
 - Pre-trigger: $\leq T$
 - Post-trigger: $\leq 4000T$
 - Resolution: $\pm \Delta t$
- Dynamic Range:** ≥ 75 dB for each full-scale range setting Measured by taking at least 16 averages of a minimum detectable signal in the presence of a full-scale in-band signal with random signal type selected and a frequency separation between signals of at least 6% of the selected bandwidth Includes distortion noise and spurious signals caused by full-scale outside energy within 200 kHz For passband mode the exact center of the passband is reduced to ≥ 65 dB from full-scale

NOISE OUTPUT CHARACTERISTICS

Type: Broadband random

Bandwidth:

Baseband Mode: Amplitude controlled dc to selected band width

Passband Mode: Amplitude controlled dc to center frequency plus one-half the band width, nominally

Output Impedance: $<1\Omega$ nominal at 1 kHz

Maximum Output Current: ± 50 mA peak

Output Level: Adjustable from 0.4 Vrms to 3.5 Vrms typically
Also 3.5 Vrms typical position

Crest Factor: 2.5:1 typical

DISPLAY CHARACTERISTICS

Number of Traces: One or two — designated A and B

Display Formats: Full (single trace), Upper/Lower (dual trace),
Front/Back (dual trace)

Active Trace: The active trace may be designated A, B, or A and B

Display Cursors: Cursors are displayed in full format as either a line or a band on the X axis, the Y axis, or both axes simultaneously. Cursors may be swept via their control keys or set to values explicitly entered by the operator.

Display Update: Display is buffered and refreshed at the line frequency rate.

MISCELLANEOUS CHARACTERISTICS

Self-Test: A self-test function is provided.

HP-IB: An optional HP-IB interface is available. A rear-panel switch selects talk only or addressable operating modes. HP-IB is Hewlett-Packard's implementation of IEEE Standard 488-1975 (Digital Interface for Programmable Instrumentation).

Remote Start: Measurement may be initiated by contact closure to ground via rear-panel BNC connector.

External Sampling: A rear-panel connector is provided for an external sampling signal at TTL levels. The frequency provided must be four times the desired range (100 kHz single, 75 kHz dual channel maximum). Internal filters may be switched out if desired.

External CRT Output: Horizontal, vertical and intensity outputs are provided to drive an external large screen display. Horizontal and vertical outputs provide a nominal range of $\pm 1/2$ volt. Intensity output provides $-1/2$ volt to $+1$ volt. Display must have a 5 MHz bandwidth.

Analog Plotter Output: A rear-panel ribbon connector provides horizontal, vertical, pen lift and servo on/off outputs to an analog plotter.

GENERAL CHARACTERISTICS

Dimensions: 64.14 cm (25.25 in.) deep, 42.55 cm (16.75 in.) wide,
40.64 cm (16.0 in.) high

Weight: 52.16 kg (115 lbs.) net

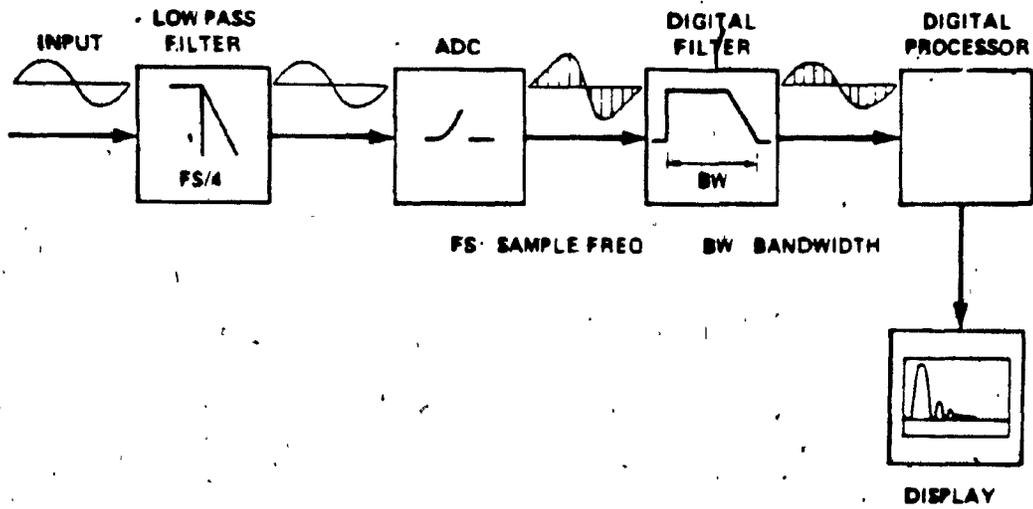
Power: 110V $\pm 20\%$, optional 230V $\pm 20\%$, 800 VA max, 1600 watts
max, 48-66 Hz

OPTIONS

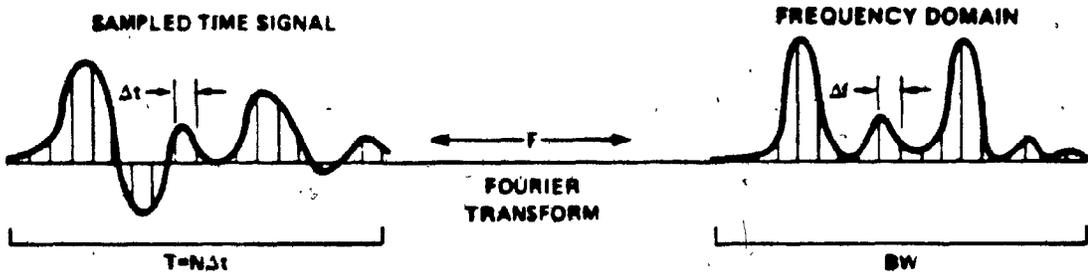
015 230 volt operation

907 Front Handle Kit

For a complete list of options, accessories, and prices consult the 5420A Ordering Information Guide.



HP5420A SIGNAL PROCESSING BLOCK DIAGRAM



TIME TO FREQUENCY TRANSFORM

Tape transport mechanism

3-motor tape drive: 3 AC driven spooling motors
1 AC driven capstan motor, electronically regulated

Tape speeds

375 ips and 7.5 ips, electronic change-over
Tolerance from nominal: $\pm 0.2\%$
With external accessory: speed variable from 25 - 11 ips

Wow and flutter

(as per DIN 45507/consistent with IEEE standard 193-1971)
at 375 ips less than 0.1 %
at 7.5 ips less than 0.08 %

Tape slip

max: 0.2 %

Reel size

Up to 10.5 inch diameter
(min. hub diameter 2.36 inches)
Tape tension switchable
(for small hub diameters)

Winding time

Approx. 135 sec for 3600 ft of tape

Tape transport control

Integrated control logic with tape motion sensor provides for any desired transition between different operating modes. Contactless electronic switching of all motors. Remote control of all functions and electric timer operation are possible.

Equalization

(as per NAB)
375 ips 90 μ sec / 3180 μ sec
7.5 ips 50 μ sec / 3180 μ sec

Frequency response

(measured via tape at -20 VU)
at 375 ips 30 Hz - 16 kHz $\pm 2/-3$ dB
50 Hz - 10 kHz ± 1.5 dB
at 7.5 ips 30 Hz - 20 kHz $\pm 2/-3$ dB
50 Hz - 15 kHz ± 1.5 dB

Peak recording level

514 nWb/m corresponds to 6 dB above 0 VU

Level metering

VU meter as per ASA standard with LED peak level indicators

Distortion

| | | |
|------------|-------------|-------------|
| at | 0 VU | 0 VU + 6 dB |
| | (257 nWb/m) | (514 nWb/m) |
| at 375 ips | < 1 % | < 2.5 % |
| at 7.5 ips | < 0.6 % | < 1.5 % |

Signal to noise ratio

(weighted as per ASA A, measured via tape)
half track
at 375 ips better than 64 dB
at 7.5 ips better than 67 dB
quarter track
at 375 ips better than 60 dB
at 7.5 ips better than 63 dB

Crosstalk

(at 1000 Hz)
Stereophonic better than 45 dB
Monophonic better than 60 dB

Erase depth

at 7.5 ips better than 75 dB

Inputs per channel

MIC (unbalanced)
position LO 0.15 mV / 2.2 kohms
for 50 - 600 ohms microphones
position HI 2.8 mV / 110 kohms
for microphone impedances up to 20 kohms
RADIO 2.8 mV / 20 kohms
AUX 40 mV / 220 kohms
Overload margin on all inputs 40 dB (1:100)

Outputs per channel

(Level at 6 dB above 0 VU / 514 nWb/m)
OUTPUT 1.55 V / R, 390 ohms
max: 1.5 kohms
adjustable with preset control
max attenuation -26 dB
RADIO 1.55 V / R, 4.7 kohms
adjustable with preset control
max attenuation -26 dB
PHONES (2 x) max: 5.6 V / R, 220 ohms
short-circuit proof
optimum matching impedance 200 - 600 ohms

Components

11 IC, 1 Opto-coupler
4 Triac, 60 transistors, 33 diodes
5 LED, 2 full wave rectifiers
3 relays

Electric current supply

100⁰ 240 V $\sim \pm 10\%$
voltage selector for
100 V, 120 V, 140 V, 200 V,
220 V, 240 V
50 - 60 Hz: without conversion
max. 80 watts
Main fuse 100 - 140 V 1 amp slow-blow
200 - 240 V 0.5 amp slow-blow

Weight

approx. 17 kg / 37 lbs 7 ozs

Dimensions

W x H x D = 452 x 414 x 207 mm
(17.8 x 16.3 x 8.14 inches)

Required clearance for 10.5" reels

max. width 538 mm (21.2")
max. height 463.5 mm (18.25")

APPENDIX C
ENGINE SHAPERS

In this section we are going to present a sample derivation of the Engines sounds shapers. Figure 5.6, 5.7, and 5.8, along with figures 5.45, 5.46, are going to be included for clarity. Examining these figures the following data tables are assembled.

| N1 RPM (percent) | Frequency component (Hertz) | Amplitude (dB) |
|---------------------|--------------------------------|-------------------|
|---------------------|--------------------------------|-------------------|

| | | |
|------|-------|----|
| 22.1 | 800. | 48 |
| 60.0 | 1785. | 57 |
| 73.4 | 2475. | 64 |
| 85.6 | 2800. | 54 |
| 91.4 | 3000. | 43 |

| N2 RPM (percent) | Frequency component (Hertz) | Amplitude (dB) |
|---------------------|--------------------------------|-------------------|
|---------------------|--------------------------------|-------------------|

| | | |
|------|------|----|
| 58.8 | 125. | 57 |
| 85.7 | 281. | 66 |
| 89.3 | 312 | 68 |
| 94.2 | 468. | 66 |
| 96.1 | 412. | 66 |

Plotting the data we obtain the shapers presented in figures 5.4, and 5.5. as well as the linear relationship between the engine RPM and the frequency of its sound. Refer to figures 5.47, and 5.48.

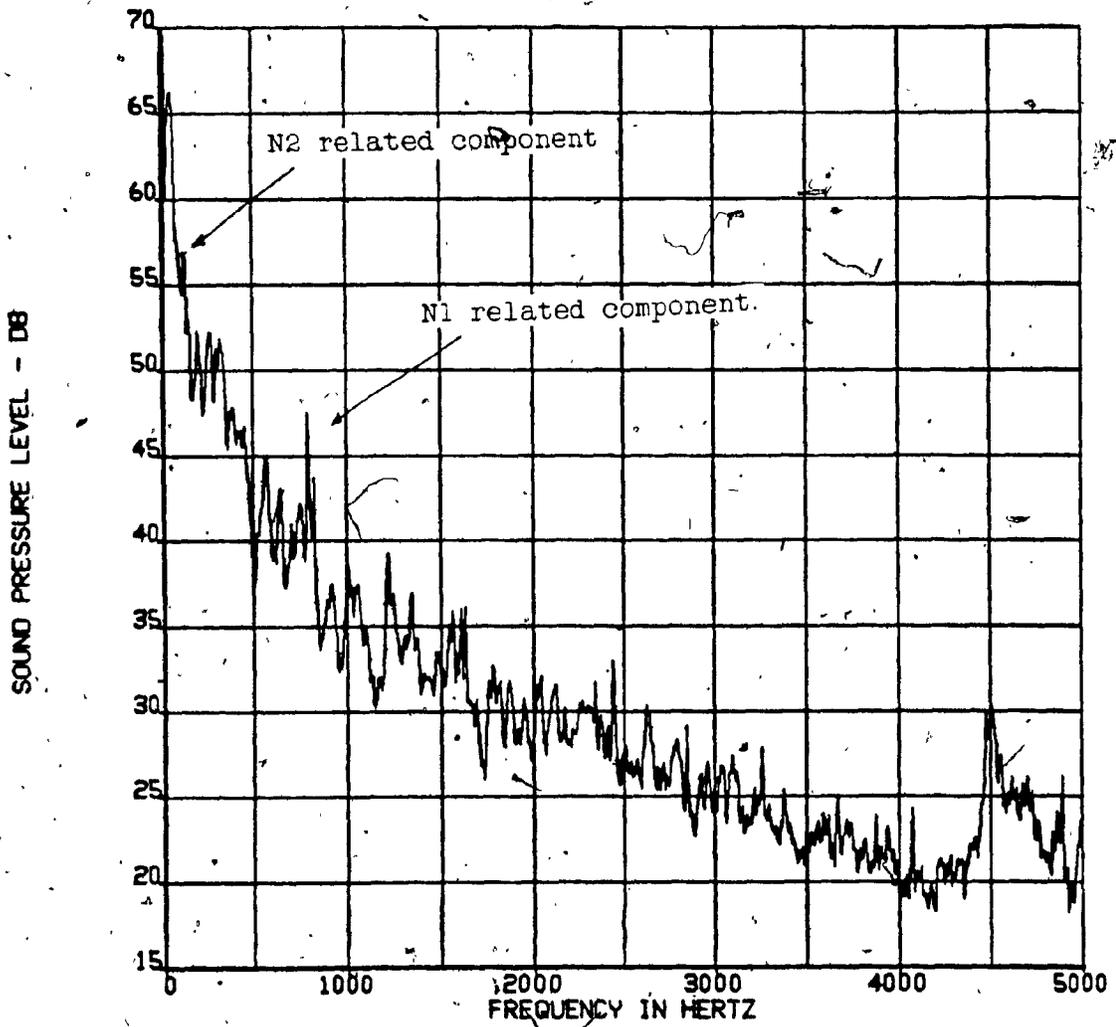


Figure 5.6 Engine RPM : N1=22.1% N2=58.8%

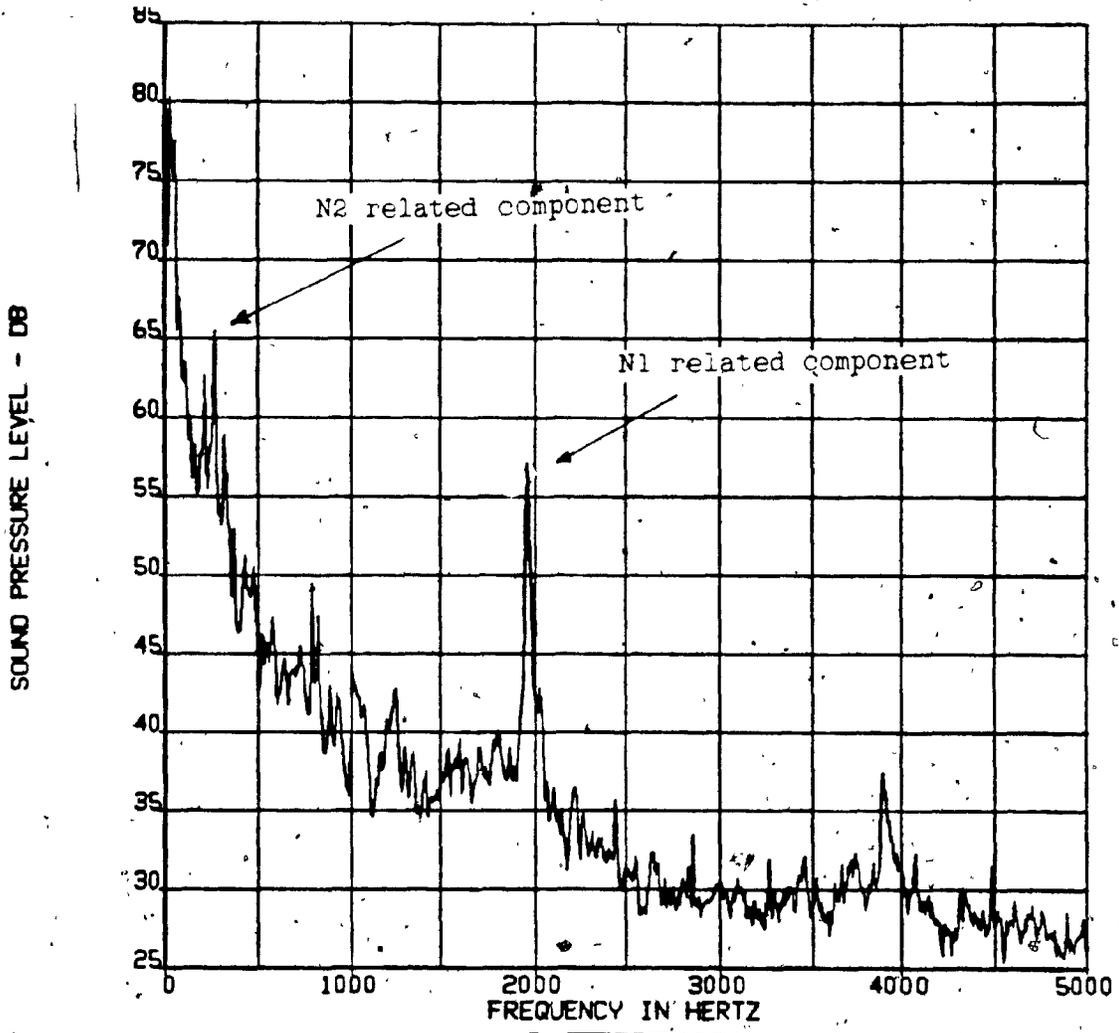


Figure 5.7 Engine RPM : N1=58.8% N2=85.7%

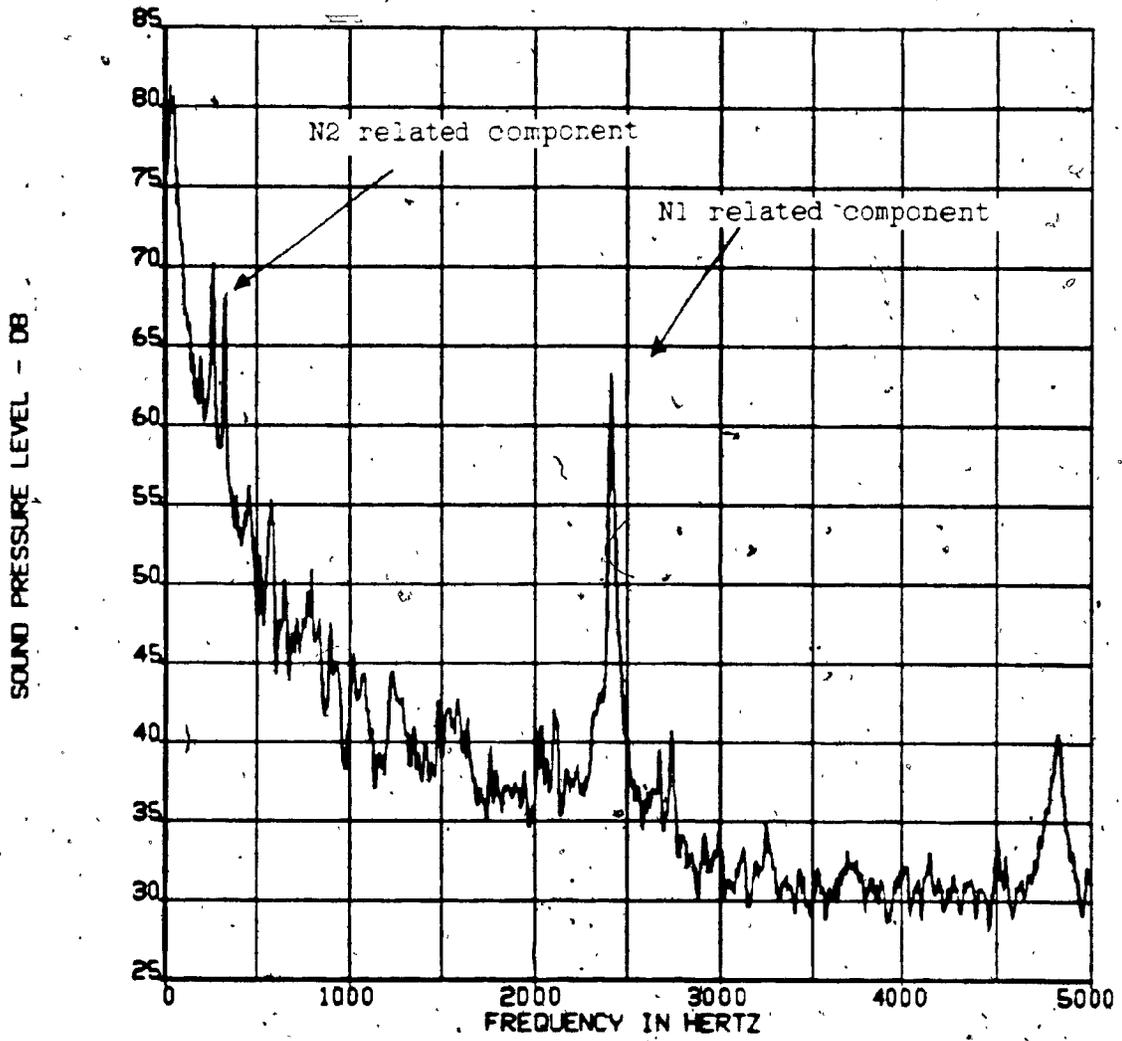
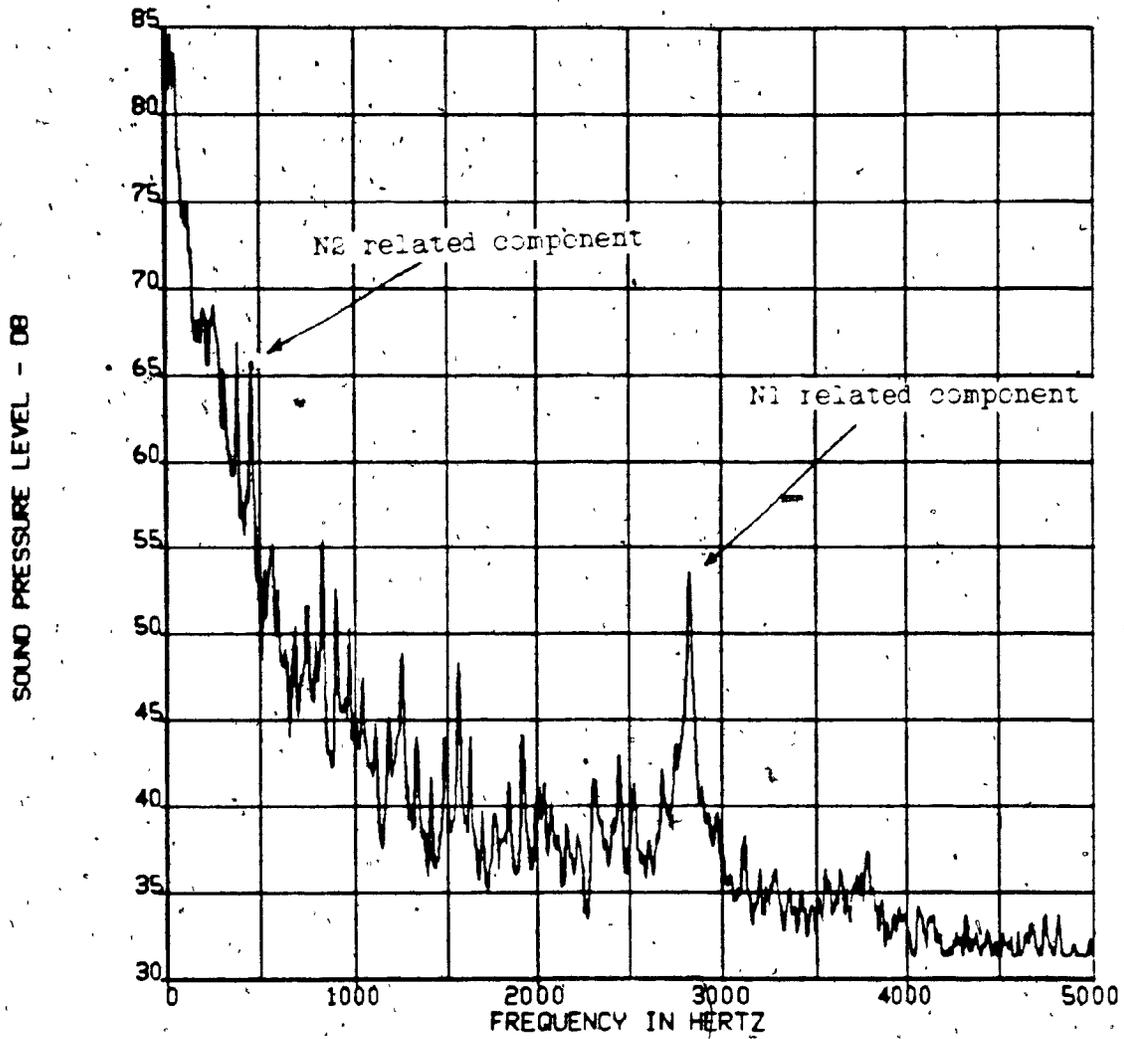


Figure 5.8 Engine RPM N1=73.4% N2=89.3%



'Figure 5 45 Engine RPM . N1=85 6% N2=94.2%'

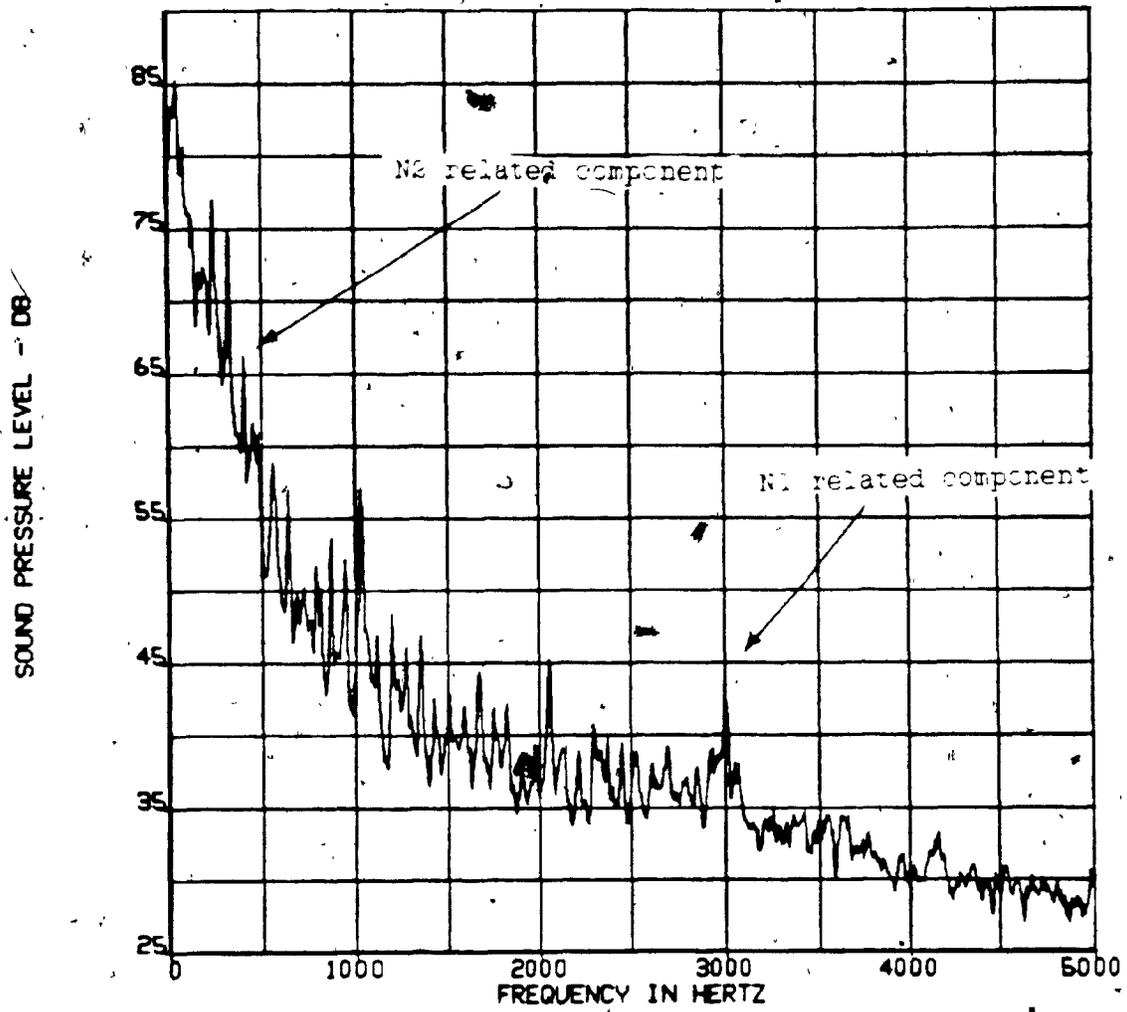


Figure 5 46 Engine RPM N1=91 4% N2=96 1%

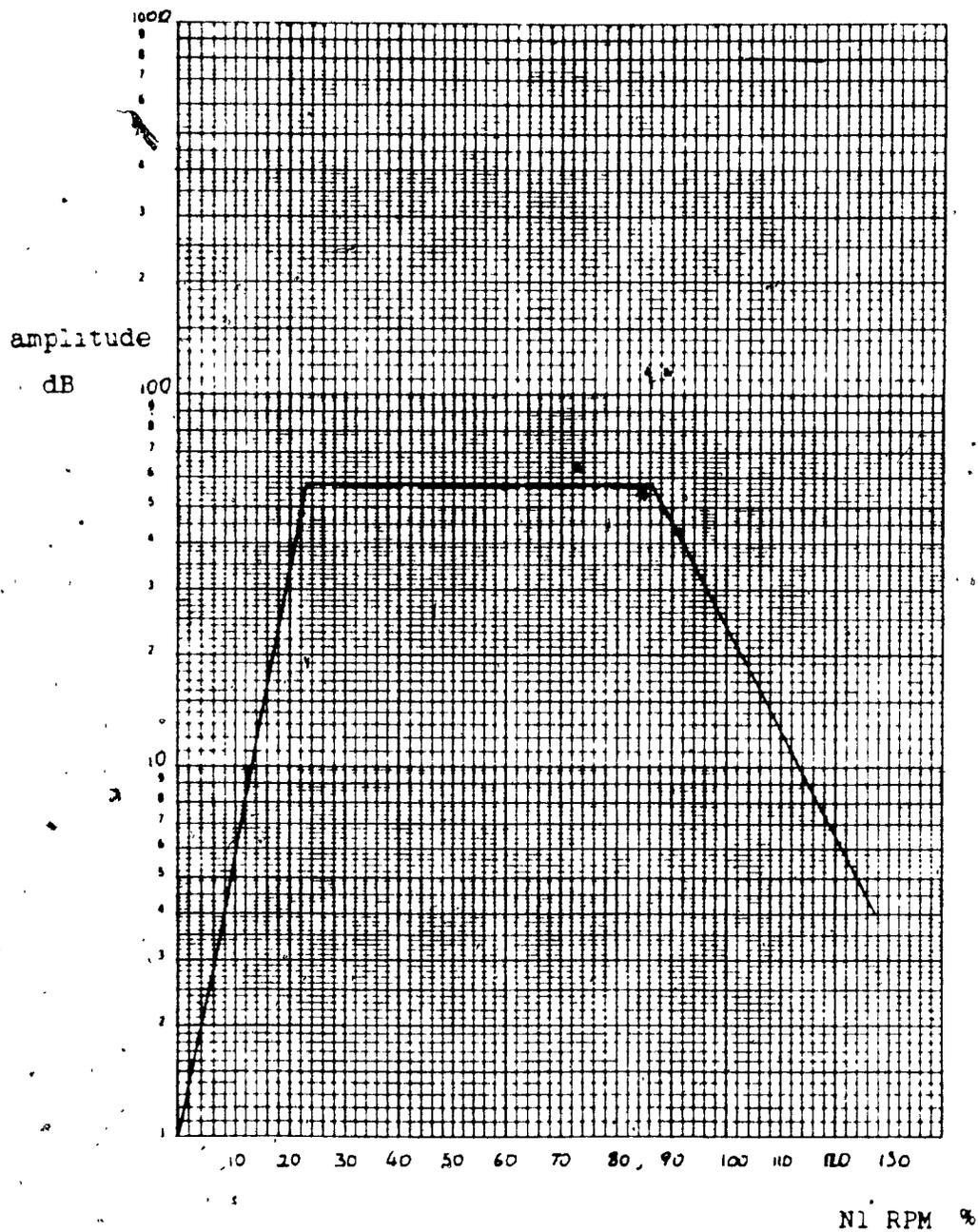


Figure 5-47 Sound amplitude vs N1 RPM

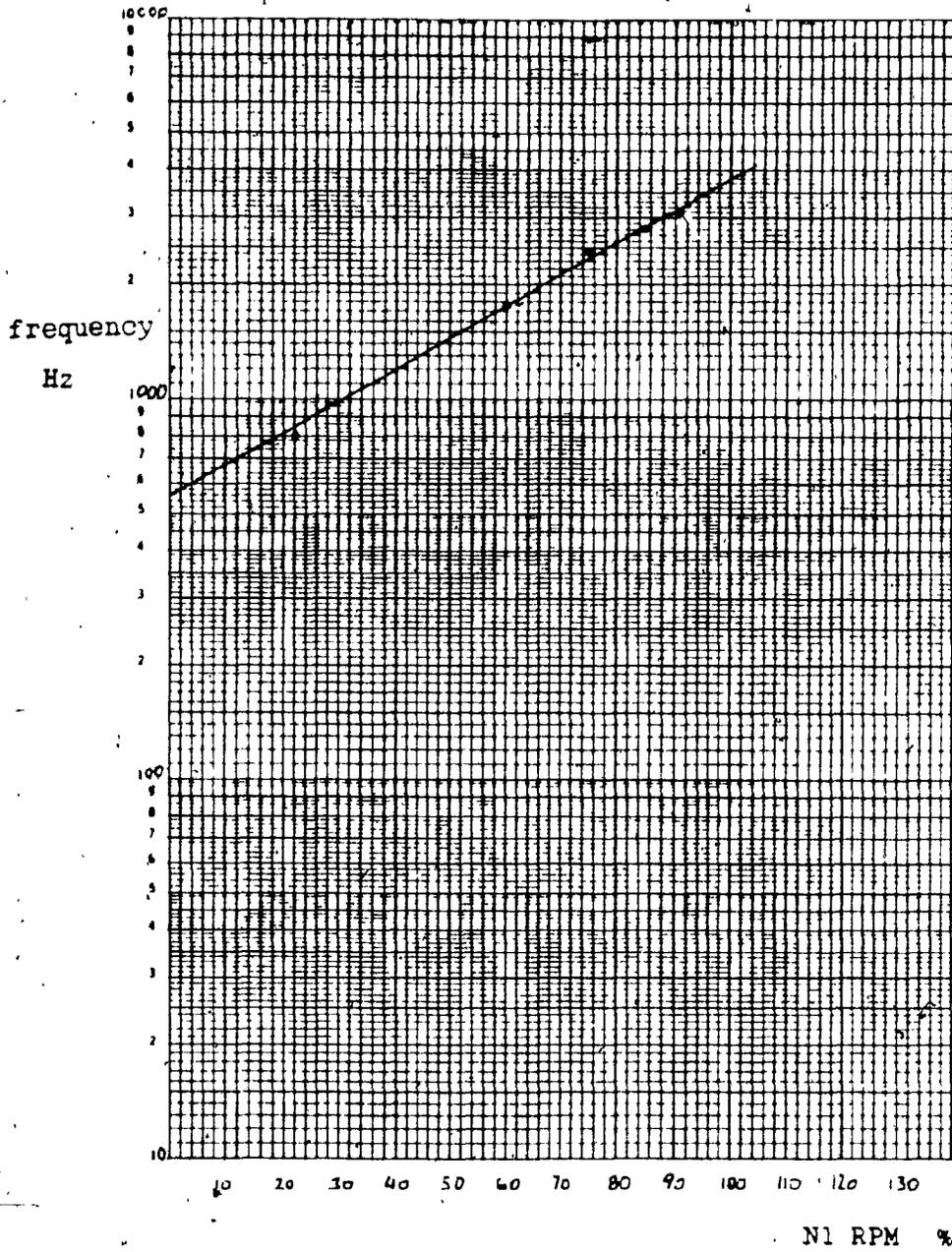


Figure 5.48 Sound frequency vs N1 RPM

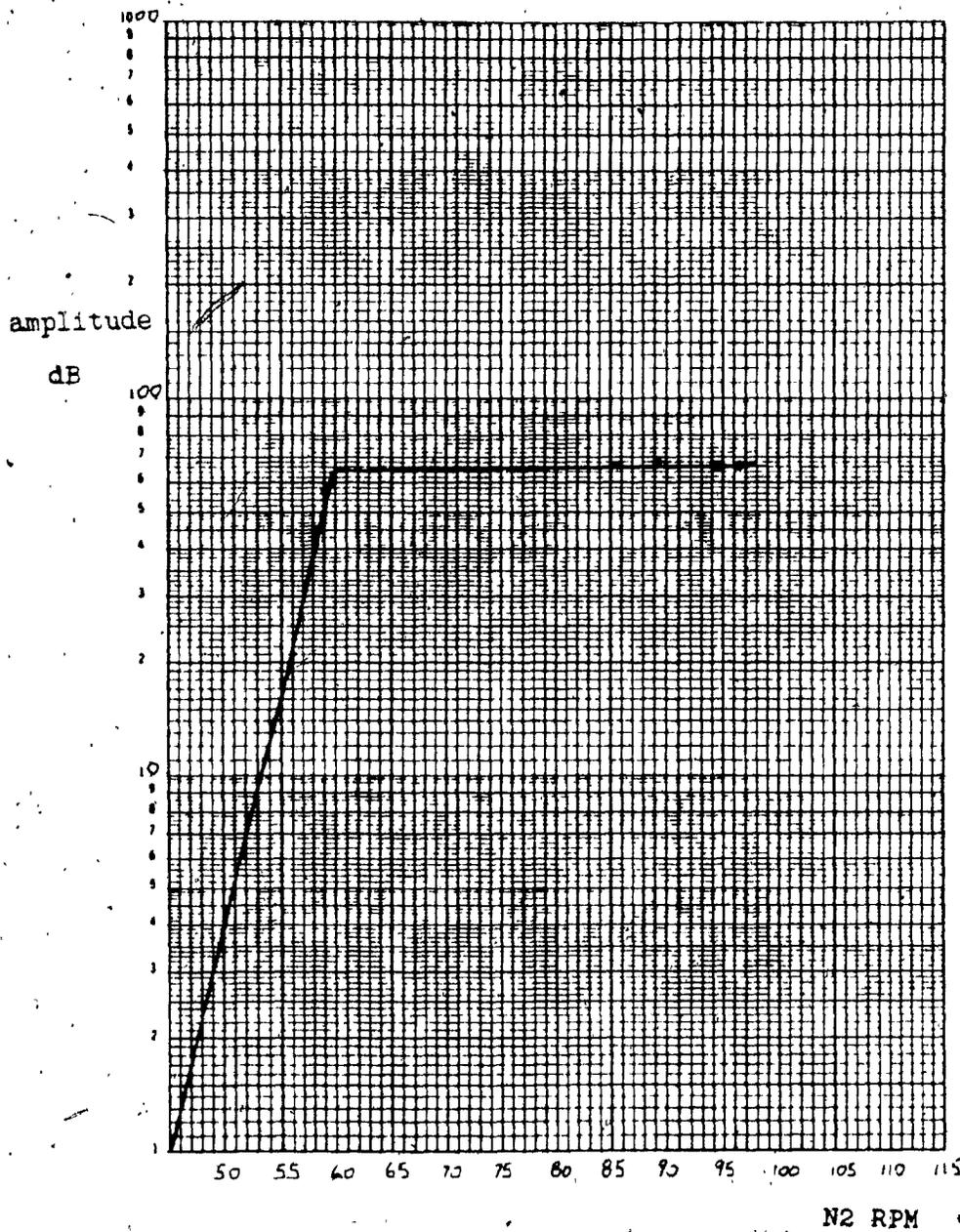


Figure 5 49 Sound amplitude vs N2 RPM

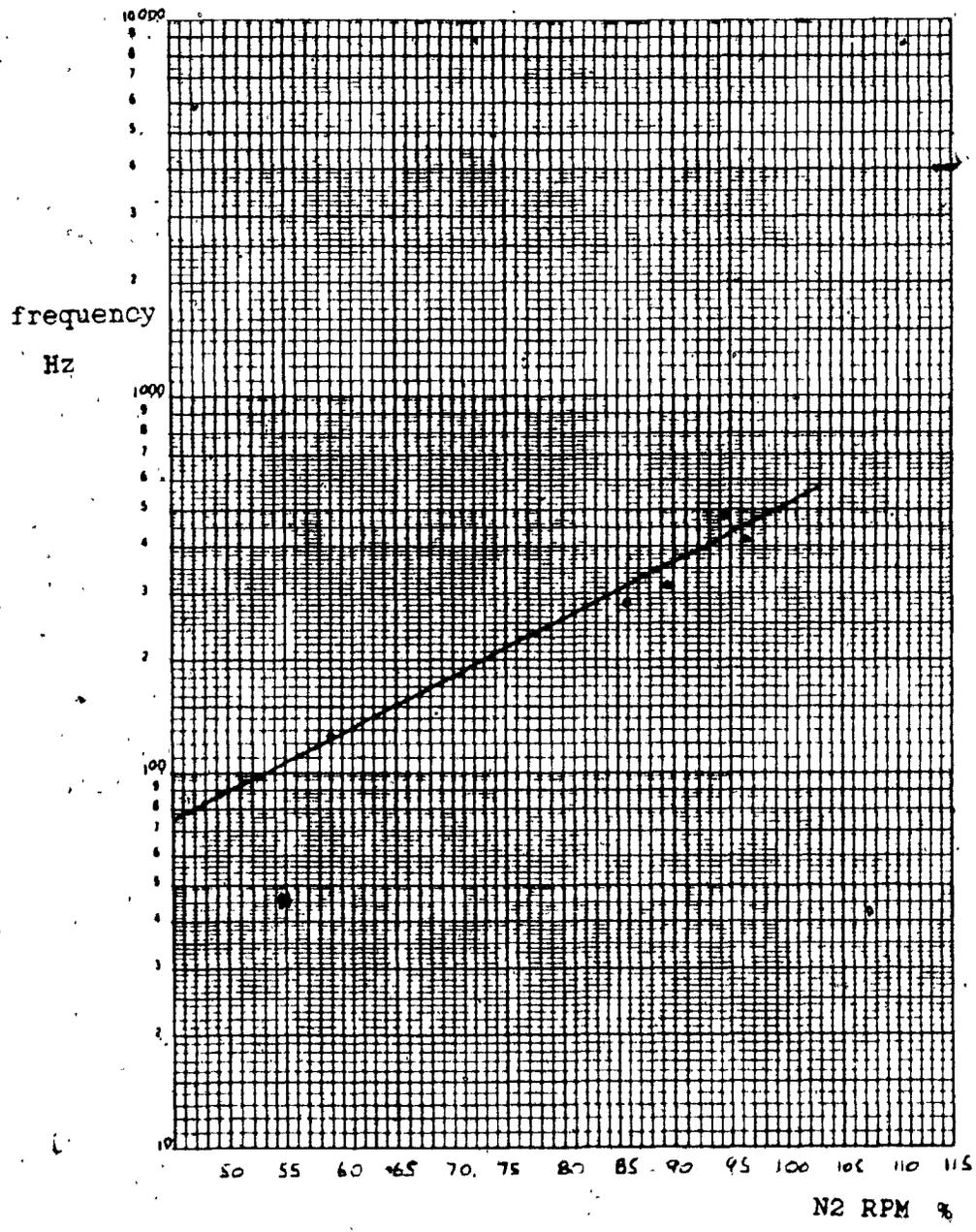


Figure 5 50 Sound frequency vs N2 RPM