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RESEARCH NEEDS IN AIRCRAFT NOISE PREDICTION

by

John P. Raney

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16. Abstract

Progress needed in understanding the mechanisms of aircraft noise generation and propagation is outlined using the focus provided by the need to predict accurately the noise produced and received at the ground by an aircraft operating in the vicinity of an airport. The components of internal engine noise generation, jet exhaust, airframe noise and shielding and configuration effects and the roles of atmospheric propagation and ground noise attenuation are presented and related to the prediction problem. The role of NASA in providing the focus and direction for much needed advances is discussed and possible contributions of the academic community in helping to fulfill the needs for accurate aircraft noise prediction methods are suggested.

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INTRODUCTION

The approach to predicting the noise generated by an aircraft for all ranges of its operating parameters depends, at present, on the acquisition of and access to a data base of measured noise data (for existing aircraft). The physical nature of the noise generating mechanisms and their interaction upon one another are not well enough understood, for example, to serve as the basis for a complete analytical model of an entire aircraft. In other words, analytical modeling of aircraft-produced noise has many stages of development ahead before it approaches the present state of the art of analytical modeling of the behavior of complex structural systems in which analysis has largely replaced testing. Since the pace of technological development most frequently has reflected the most urgent needs of mankind, this state of affairs may not be too surprising. Only fairly recently has noise of all forms become of real concern to large numbers of the population. Therefore, far from being a mined-out field capable of admitting only infinitesimal future advances, aircraft noise prediction technology offers the intrepid researcher significant challenges and rewards in nearly every direction.

The purposes of this paper are briefly to give an overview of the aircraft noise prediction problem, to highlight NASA's role in aircraft noise prediction, to discuss present methods of noise prediction, and to suggest some critical areas and directions for future research that will provide orderly improvements in the state of the art of aircraft noise prediction.

AN OVERVIEW

The aircraft noise prediction problem can best be described with reference to figures 1 and 2. The problem is adequately to describe the aircraft as a noise source within an appropriate coordinate system and to compute the received noise in terms of a variety of scales in common usage. The ingredients of the problem may be subdivided into the two broad categories of source noise description and propagation effects. Given the source characteristics and the propagation effects, the received noise is uniquely determined.

Source Noise Description

In order to be described as a noise source, the flight profile and operational parameters, the noise radiation patterns of the engines, the reflection and shielding characteristics, and the airframe generated noise pattern of the aircraft must be known. The resulting source noise description is a complex, time-varying phenomenon with directivity, frequency content, and sound pressure levels constantly changing. Some of the information required to generate aircraft source noise models will be discussed in the following paragraphs.

Flight profile and operation parameters.- In order to compute received noise, the location of the source must be known (fig. 1). The position of the aircraft at any time is nominally determined by the aircraft and engine performance parameters, and the airport and airline operating procedures. Ideally, each takeoff of a given type of aircraft, for example a Boeing 727-200, at a given weight from the same airport and runway, for example runway 27 at Chicago O'Hare, should follow the same flight profile — and, thus, generate a noise history identical to other 727-200's at the same takeoff weight using the same runway.

Among the operational parameters of interest is the engine thrust setting which determines the engine noise level and which itself is determined by aircraft weight and the desired flight profile. Other parameters required as input to the noise source determination problem include flap setting, landing gear position, and aircraft attitude. With the takeoff weight and flight profile known, the necessary aircraft configuration, airspeed, attitude, and thrust setting versus time are very nearly uniquely determined for a given aircraft. Together with aircraft position the latter four variables are required to initiate computation of the noise source characteristics of the aircraft.

Airframe and engine flow-field characteristics.- When the flight profile and operational parameters have been determined, airframe and engine flow field parameters may be computed. Knowledge of the flow field characteristics over the surface of the aircraft and through the engine is required in order to provide accurate values of parameters necessary for the computation of surface flow (airframe) generated noise and engine internal noise.

Engine noise characteristics.- The major noise generating mechanisms in the engine are associated with the fan, the turbine, the combustion chamber, and the jet (fig. 2). Internal aerothermodynamics and duct acoustic analyses provide the required inputs to models of engine noise generation and suppression mechanisms. Of course, the powerplants of V/STOL aircraft may involve propeller or rotor noise as well as surface blowing noise mechanisms.

Airframe noise.- Although the aerodynamic (airframe) noise levels are presently lower than the noise level of the powerplant, further significant powerplant noise reduction will result in greatly increased significance of the airframe noise. Airframe noise must be considered a major contributor to an aircraft's noise description especially for terminal (i.e., landing and takeoff) configured operations.

Shielding and reflection.- Engine noise radiation patterns interact with and are affected by the presence of other engines on the aircraft by the aircraft structure. The aircraft structure may block noise radiation in a certain direction and create a new source by reflecting it in other directions. The complex interaction of aircraft structure with powerplant generated noise may significantly affect the characteristics of the total source noise description. The presence and location of additional engines creates multiple source interactions for which account should be made.

Propagation and Surface Effects

Aircraft noise must be propagated through the atmosphere and, in some situations, experience surface interactions before reaching an observer on the ground. Atmospheric parameters of interest include temperature, pressure, and relative humidity together with relative velocity and turbulence. Ideally, the atmospheric state vector should be known along any propagation path of interest. A suitable micromodel of the atmosphere near an airport may, therefore, be required to support relatively precise computations of atmospheric effects such as molecular absorption and turbulence scattering. Surface effects include the surface or ground impedance and roughness, for example, so that the nature of sound reflected to the receiver can be determined.

Received Noise

With the source noise characteristics and sufficient atmospheric parameters in hand, the nature of noise at a receiver can, presumably, be uniquely determined for a single aircraft flyover. The received noise thus determined for each of any number of unique types of flyover events can then be further processed (integrated over time and frequency and number of events) in accordance with any of several algorithms to produce indices of cummulative received noise.

NASA'S ROLE IN AIRCRAFT NOISE PREDICTION

In 1973, NASA established an Aircraft Noise Prediction Office (ANOPO) at the Langley Research Center. The purpose of creating this new organization was to provide both a focal point for NASA's aircraft noise prediction activities and an appropriate interface with other agencies and industry. In addition, the ANOPO charter directs the timely creation of a new, integrated, user-oriented state-of-the-art Aircraft Noise Prediction Program (ANOPP). ANOPP will be specifically tailored to meet NASA's requirements for aircraft noise prediction and will be used extensively by NASA to evaluate and quantify the benefits expected from proposed noise reduction projects and research activities.

The results of some of ANOPO's activities related to determining the state of the art of aircraft noise prediction and the requirements of ANOPP users are discussed below. The characteristics of a comprehensive prediction capability which appears to be both desirable and feasible are also presented.

Interim Noise Prediction Capability

In support of the preparation of a viable ANOPP development plan

ANOPO has acquired and installed at Langley an interim system for aircraft noise prediction consisting of a family of contemporary, independently developed capabilities as follows (see fig. 3):

A. (1) An aircraft source noise modeling program written by the Boeing Company for the NASA Ames Research Center [1], [2]

(2) An aircraft engine noise synthesizer developed by the Noise Effects Branch of the NASA Langley Research Center

B. A Noise Exposure Forecast (NEF) contour program written by Bolt Beranek and Newman (BBN) for the United States Air Force [3]

C. An NEF contour program written by Wyle Laboratories for the Department of Transportation

D. An extensive data base of noise data for the civil fleet prepared for the FAA [4], [5]

The interim programs are presently being utilized by ANOPO, by Langley project offices, and occasionally by other Government agencies. Some of the elements of the interim programs may be selected for incorporation in ANOPP; however, the interim programs themselves will eventually be discarded in favor of a more comprehensive and flexible ANOPP system.

Key Technology Documents

In order to assure that state-of-the-art technology is implemented in ANOPP, a series of noise prediction technology documents are being generated with the cooperation of other NASA centers, other Government agencies, and industry. These documents bear approximately a one-to-one correspondence to the functional (or computational) modules planned for ANOPP. The areas covered by individual documents are shown in figure 4.

The continually updated Key Technology Documents combined with inputs from periodic NASA/User Seminars will constitute the mechanism for assuring the implementation of current prediction technology in the ANOPP system.

Potential Users

Contacts with NASA Headquarters and other agencies together with the Key Technology Document activity have helped ANOPO identify potential users of ANOPP. Several classes of user have emerged whose primary interests are indicated below:

USER	Source Noise Modeling Design	Single Event Exposure	Multiple Event Cumulative Exposure
NASA	✓	✓	✓
FAA	✓	✓	✓
DOD	✓	✓	✓
Engine Manufacturers	✓	✓	
Airframe Manufacturers	✓	✓	
EPA			✓
Airport Managers			✓
Consultants			✓
Universities	✓	✓	✓

The needs of ANOPP users range from sophisticated analytical source modeling and design to empirical computation of cumulative noise exposure. Some users will wish to use ANOPP only in connection with making community exposure estimates and sensitivity studies related thereto. An engine design group might be interested in analysis and evaluation of possible engine configurations based on analytical models of noise generating mechanisms. Analog or one-third octave data will be required by the latter and noise level vs distance by the former.

ANOPP Logical Levels

As shown in figure 5, ANOPP will provide four logical levels of computational sophistication intended to satisfy the needs of various user groups and to provide a self-contained systematic means for validating and improving the state of the art of aircraft noise prediction.

Level I (fig. 6), the simplest operational mode of the program, is intended to serve civil engineers and community planners who have minimal knowledge of the complex technology of aircraft noise prediction. This level of ANOPP is characterized by the use of time-integrated flyover (Noise, Thrust, Altitude) data in such units as EPNdB to compute measures of community noise environment such as NEF contours. The AF-BBN and DOT-Wyle programs operate at this level.

Level II (fig. 7) of ANOPP is intended to serve aeronautical engineers in making systems studies involving general aircraft types as well as the noise control engineer who requires greater knowledge of the community aircraft noise exposure than the time-integrated estimates provide. Level II is based on the use of computed or measured values of noise levels such as PNdB's and dBA's which vary during the aircraft flyover. There are no generally useful existing programs which use this prediction methodology.

Levels III (fig. 8) and IV (fig. 9) of ANOPP will be used to predict the time-dependent noise spectrum from an analysis of the aircraft component noise sources and an analysis of the aircraft flight. These levels are intended for the use of engineering and research specialists in aircraft noise. Level III is at present based primarily on empirical formulas for the noise of different aircraft source components. This level will be suitable for making detailed systems studies of aircraft/engine configurations. The NASA-Boeing program operates at this level. Level IV will be the repository for the most advanced acoustical technology and may be used in an experimental sense for technology validation and improvement or for detailed designs of advanced low-noise components for aircraft.

PRESENT METHODS

Present methods of aircraft noise prediction include empirical implementation of Level I and Level III. The most reliable method in current use is Level I which involves the measurement of noise for known flight conditions (level flight) and then prediction of ground noise conditions for the operational envelope of the airplane from interpolations and extrapolations of the measured data base. One difficulty is that such data are available for specific conditions only after the aircraft is flight operational and are not, for example, derived from integrating Level IV or Level III results.

The present Level III methods of aircraft noise prediction are, for the most part, typified by algebraic expressions which have been fitted to experimental data. The interim prediction methods recommended in published Key Technology Documents serve as a case in point (refs. 6-11). For example, the sound power level prediction for low frequency core engine (combustion) noise (ref. 6) is given in terms of mass flows, pressures, and temperatures as

$$OAPWL = 56.5 + \log_{10} \dot{m}_a \left[(T_4 - T_3) \frac{P_3}{P_o} \frac{T_o}{T_3} \right]^2$$

P - pressure

T - temperature

$\dot{m}_a$ - airmass rate of flow

0 - atmospheric or free stream

3 - combustor inlet station

4 - combustor exit station

The prediction equations for fan and compressor source noise (ref. 7), jet noise (ref. 8), externally blown flap noise (ref. 9), airframe noise (ref. 10), and atmospheric propagation (ref. 11) also involve empirically derived algebraic expressions in terms of the physical variables. These expressions are not solutions to the governing equations which describe the physical system. They are the result of correlations of expressions involving the system parameters with available experimental data, must be modified whenever new data become available, and are seldom fully acceptable to persons other than the originators.

It is worth noting that, while they are not solutions to the governing equations, the present empirical expressions, which typify Level III of ANOPP, at least imply that acoustical power is proportional to mechanical power. As with the present Level I implementation, Level III predictions rely on experimental data and not on integrating Level IV results.

RESEARCH NEEDS AND DIRECTIONS

In order to develop quieter aircraft designs one of the greatest needs is the ability to predict the noise from an aircraft in flight based on a knowledge of the physical characteristics of its powerplant, its configuration, and its operating conditions. The primary goal of research in aircraft noise prediction should, therefore, be the development of the analytical approach of Level IV based on a thorough understanding of the physical mechanisms of noise generation by an aircraft propulsion system and the aircraft interacting with the air. This method — a design capability through analytical modeling — is the ultimate objective in aircraft noise prediction.

Analytical Model Development

Areas for which analytical models are needed are listed in figure 4. A legitimate source for generation of at least some of these models would appear to be the university community. A typical cycle for model development might be as shown in figure 10 which is uniformly applicable to the topics listed in figure 4.

The meaning of figure 10 is that analytical model generation should precede and be used to guide the design of experiments. On the analytical model side the first decision diamond asks whether or not solutions can be economically obtained for the proposed model. The second decision seeks to confirm the direct measurability of the model parameters. Finally, the third decision asks whether the model produces engineering results applicable to real-world physical situations — in other words are the results of practical or merely academic interest?

On the experimental validation side of figure 10 the first decision diamond asks if the experiment is motivated by the need to validate an analytical model. The second decision asks whether the experiment will lead to the understanding of an important phenomenon. It is essentially the same question asked by the third decision diamond in the analytical model generation cycle but lies within the domain of the experimentalist.

Pitfalls to be Avoided

A pitfall to be avoided is generating analytical models which, although intellectually stimulating, have compromised realistic representation of the actual physical problem in order to obtain a solution. Another pitfall to be avoided is designing experiments which merely demonstrate ability to build a physical analog of a differential equation. Only if the above activities can be shown to be necessary intermediate steps to engineering results should they be pursued.

At this point an example may be helpful. A solution to an analytical model often may be expressed in many equivalent alternative forms. Suppose a series of mathematical functions are used to represent the acoustic pressure at some point. An expenditure of significant resources to demonstrate the ability to generate these functions experimentally may have little payoff unless it directly contributes to a better understanding of the actual acoustics of a turbo-fan engine. Furthermore, if the model for which the solution may be expressed in terms of these functions is overly idealized the whole effort may result in intellectual satisfaction and little else. For example, the manufacture and study of spinning modes may eventually contribute to the ability to predict the noise generated by a proposed aircraft if those who are engaged in this activity do not lose their overall perspective of the need for obtaining engineering results. However, spinning modes in their own right are about as interesting as sine waves or Bessel functions.

Research Needs

This section of the paper should, ideally, contain a list of acoustical phenomena or processes — sorted by order or importance, difficulty, and resource requirements — for which analytical models need to be developed. Although a completely definitive catalog will not be presented, a few critical needs related to the prediction of CTOL (conventional takeoff and landing) noise will be highlighted. These areas are flow-field interaction, fan noise, combustion noise, turbine noise, duct acoustics, jet noise, airframe noise, and the propagation of noise to the reciewer.

The noise from a CTOL aircraft is generated by the engine and the airframe. In the past, engine noise has been the dominant source, but improvements in engine acoustic design promise to reduce engine noise to levels equivalent to airframe noise. Each of these sources mentioned above is controlled to a large degree by the flow field within the engine. It is apparent then, that a firm knowledge of the fluid mechanics of the engine is essential to a knowledge of the acoustics of the engine.

Flow field.- The first step, then, in improving the ability to predict noise, is to build a consistent and complete aerothermodynamic model for the aircraft engine. This model requires a general thermodynamic balance of the different stages of the engine cycle, a description of the turbulent atmosphere being drawn into the engine inlet, the flow and flow gradients in the engine ducts and blade rows, and the wall boundary layers and blade wakes. When this information is developed, the work on the acoustics problem of the engine may begin.

Fan noise.- The details of the flow field discussed above are especially important for fan noise prediction. Large-scale atmospheric turbulence is drawn into the engine inlet causing a nonuniform axial flow into the fan blades. As the blades rotate, this nonuniform flow causes unsteady loads on the blades due to the varying angle-of-attack. These unsteady loads radiate dipole noise in harmonics of the blade passage frequency. They also generate broadband noise due to the random fluctuations of the blade load amplitudes and phases. This noise caused by inlet flow distortion has been identified as a key technology area (ref. 7) for which research is needed. The understanding of both the fluid mechanics and the acoustics of the inlet flow distortion problem is necessary for advancing the state of the art of fan noise prediction.

Combustion noise.- The unsteady combustion process in the engine generates a low frequency noise which has sometimes been confused with low-frequency jet noise. The available prediction theory for this noise is empirical in nature and does not account for the fact that this noise must be carried through the turbine and exhaust nozzle before it is radiated to the far field. In order to better understand this phenomenon, a good understanding of the flow through the turbine and exhaust nozzle and the effect of this flow on the combustion noise transmission is required (ref. 6). Again, basic thermodynamics and fluid mechanics are an inseparable part of the acoustic prediction problem.

Turbine noise.- Like combustion noise, turbine noise is presently predicted by empirical formulas which account for only the gross variables of the problem. The few analytical models which have been attempted use concepts similar to fan noise in which the blades are replaced by concentrated dipoles which represent the unsteady blade loads (ref. 12); however, such models may be completely inappropriate in a turbine with high solidity stages of highly cambered airfoils. The presence of many stages in the turbine greatly attenuates the sound of all but the last stage so that the sound generation and transmission process in the turbine is quite complicated. A fundamental approach based on realistic models of the turbine flow is needed for turbine noise prediction. Turbine noise radiation is also influenced by the unsteady flow field of the jet (ref. 13). Tones generated by the turbine are transformed into broadband noise as they radiate through the unsteady turbulent jet flow. This process has been called "haystacking" because of the characteristic shape of the broadband noise which results from this process. In turbine noise, an understanding of this effect of unsteady turbulent flow on sound propagation, is required for improvement of our predictive ability.

Duct acoustics.- Noise from sources inside of the CTOL engine may be attenuated by the addition of sound-absorbing material inside the nacelle. Very precise complex analytical models of the duct transmission (ref. 14) have been developed; however, these analyses are for idealized duct and flow models. In an actual engine, the duct wall boundary layer significantly affects the attenuation of the sound, especially in the inlet. Thus again, a realistic description of the flow is necessary before a prediction can be made. Also these precise analytical models of duct transmission are based on a linear boundary condition, the duct wall impedance. It is known that the acoustic materials used in engine nacelles are nonlinear (ref. 15) at the sound intensities which occur in these engines and that the flow over the materials (ref. 16) has a major influence on this property. Thus, a primary area where work is needed in duct acoustics is the modeling of duct problems with realistic nonlinear boundary conditions.

Much of the work in duct acoustics in the past 10 years has been developed using the modal theory of sound transmission. Unfortunately, researchers have carried idealized mode transmission analyses to extremes, making predictions of attenuation based on a single mode assumption. Attempts have also been made to generate pure modes in the laboratory in order to verify their properties. Real engine noise sources, however, are always represented by a large number of modes interacting in a complex (ref. 17) manner and this must be accounted for in any realistic prediction attempt. The modeling of real sources as well as real boundary conditions is necessary for improving the state of the art in duct acoustics. Also, modal theory is not essential to the duct propagation phenomenon, it is only a tool. Other tools are now being considered. One which shows promise is the finite element method which has reached a high level of development in the field of structural analysis. Just as duct acoustics modal theory evolved from electrical transmission line theory, the finite element techniques of structural analysis may be developed into an acoustic transmission line theory which will be competitive with modal theory in the prediction of duct acoustic effects. The development and comparison of both of these methods is a fertile area for further research.

Jet noise.- Jet noise is one of the oldest subject areas of concern in the overall CTOL noise problem. In spite of this, our predictive capability for real-world jet noise problems is not well developed. Presently, an empirical formula is being used by the NASA for jet noise predictions. The difficulty with empirical formulas is that each is derived to represent only a certain set of data. The SAE A-21 committee, for example, has an empirical jet noise prediction formula which no doubt represents their data, however, the NASA and SAE predictions are different. They are different because they are based on different data. In order to eliminate these differences, it is necessary to develop a unified data base for jet noise. The data which are entered into this base should be required to meet certain standards established by the peer group of experimentalists in this field. These experimental standards will rule out certain carelessly conducted experiments and define the subset of jet noise data which will be included in the jet noise data base. The gathering of this information will also define additional experiments to be carried out. Then, if an empirical correlation is made, only one formula may be considered "best." This is the formula with the least variance of the estimate.

A unified data base will also serve to define the direction that analytical work in jet noise should take. If empirical formulas are inadequate, analytic models based on Lighthill's, Phillip's, or Lilley's equation may be used. In these partial differential equations, the source terms <u>must</u> be modeled by some assumed turbulent flow. Here again, the basic fluid mechanics of turbulent flow enters the picture. It is necessary to compare a sequence of models for the source terms in both Lighthill's, Lilley's, and other jet noise formulations to see which provides the least variance of the estimate against a unified data base. When comparing the solutions to partial differential equations, however, the accuracy of the prediction is not the only criterion which may be cited to determine which of several methods may be best. The <u>cost of prediction</u>, as judged by computation time, for example, is another factor which must be considered. Perhaps the most important consideration of all is, "does the predictive equation provide a realistic method for achieving noise reduction?" All of these factors must be considered in arriving at a "best" jet noise prediction method.

Airframe noise.- Besides the engine, the various components of the airframe may radiate significant amounts of noise during the landing approach of a CTOL aircraft. Here again, we are at the empirical formula level in our state-of-the-art prediction capability. Presently, we use a formula (ref. 10) developed for aircraft in the "clean" configuration from a limited, but well defined, data base. It is recognized that the extension of flaps and landing gear will increase the airframe noise by 10 dB or even more so that the present prediction method is an interim device used for order-of-magnitude estimations. A promising empirical approach which accounts for the effects of flap extension is the drag element noise theory (ref. 18). In this theory, each airfoil is assumed to produce a noise in proportion to the cube of its drag coefficient. This theory is related to the analytic theory of edge noise (ref. 10) which is probably the dominant component of airframe noise. Edge noise theory depends on the turbulent flow conditions at the trailing edge of an airfoil, though, so we see a fundamental dependence of the acoustics of airframe noise on the fluid dynamics of the airfoil. Research in this field must proceed along a consistent path using valid models of the turbulent boundary layers in comparably valid acoustic theories. Experiments in edge noise must simultaneously study the fluid dynamics of the turbulent flow and the noise radiation. Precise flight tests are also required to validate empirical theories such as the drag noise theory.

Noise propagation.- CTOL noise must propagate over large distances before it reaches the community. The character of the noise is modified during this propagation process due to the dependence of attenuation on such factors as frequency, temperature, and humidity. Fortunately, available prediction methods (ref. 11) account for the more important absorption processes, classical absorption and molecular absorption, if the ambient atmospheric conditions are known along the ray from the source to the observer. There remains some controversy about the effects of atmospheric turbulence on propagation which must be resolved by careful experimental work. A more important research area relates to the effects of ground absorption on the propagation of sound. There is a strong theoretical base for prediction of ground absorption, but these prediction methods depend on the impedance of the earth surface which is seldom, if ever, known. Thus, careful studies are required to develop a data base of ground impedance data for the various types of terrain which are involved in the aircraft noise propagation problem. The development of these data by careful experiments will greatly improve the accuracy of our noise prediction methods.

In summary, the research needs in aircraft noise prediction can best be satisfied by systematically developing analytical models for all the topics listed in figure 4. Rigorous application of the criteria of figure 10 to the topics of figure 4 will most rapidly advance the aircraft noise prediction engineer from ex post to ex ante capability.

CONCLUDING REMARKS

Advancing the state of the art of aircraft noise prediction requires, most of all, great emphasis on first achieving a thorough understanding of the physical mechanisms of noise generation and propagation. This understanding can best be gained through the process of formulating practical analytical models in terms of parameters which can be measured in high quality experiments designed with the requirements of model verification in mind.

The role of universities is obvious. Universities possess the talent to conceive analytical models of complex physical phenomena and to design experiments for the verification and refinement. University participation can, therefore, both assure and hasten the attainment of a mature capability accurately to predict aircraft noise.

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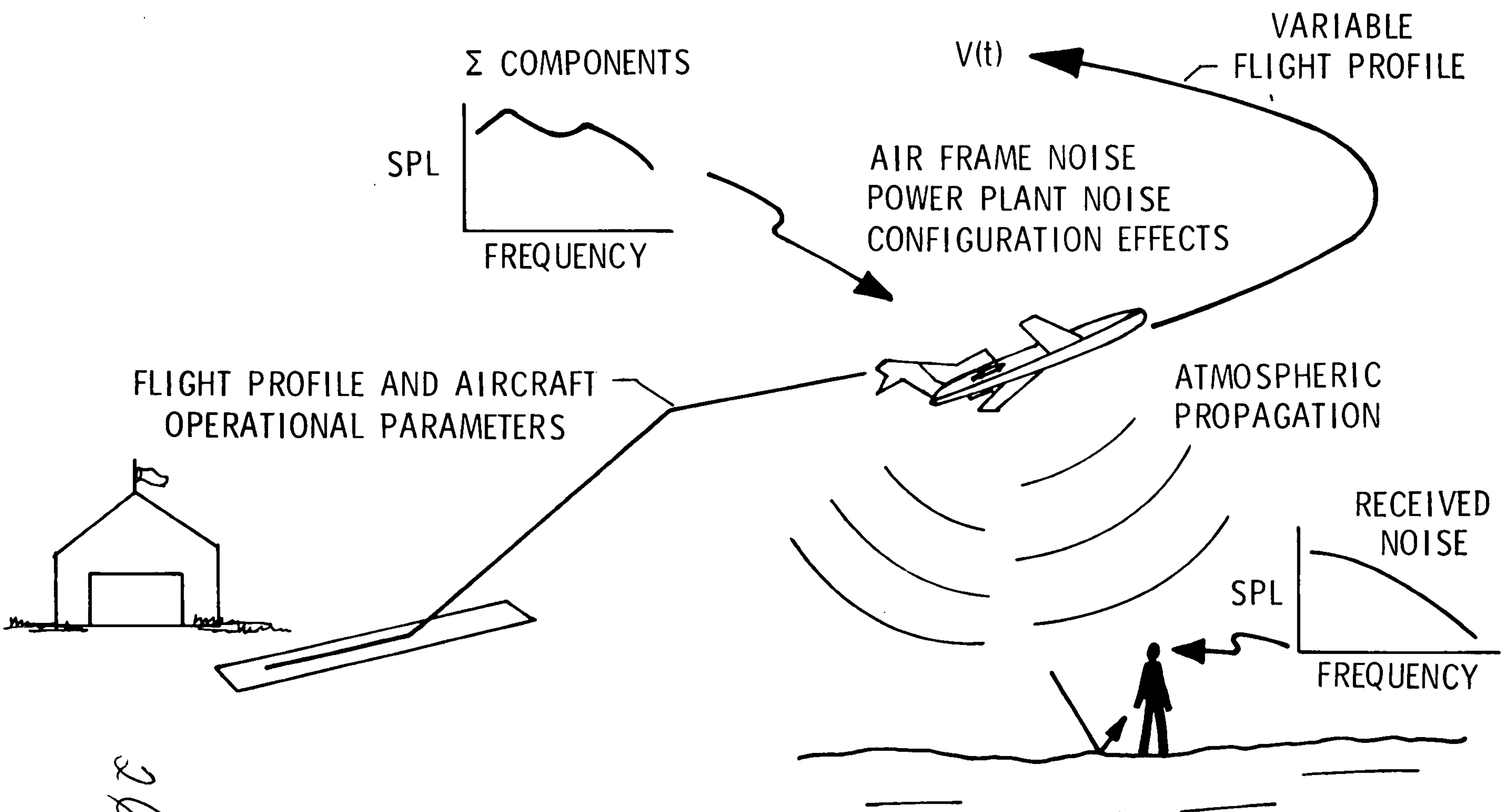


FIG. 1 AIRCRAFT SOURCE NOISE DESCRIPTION.

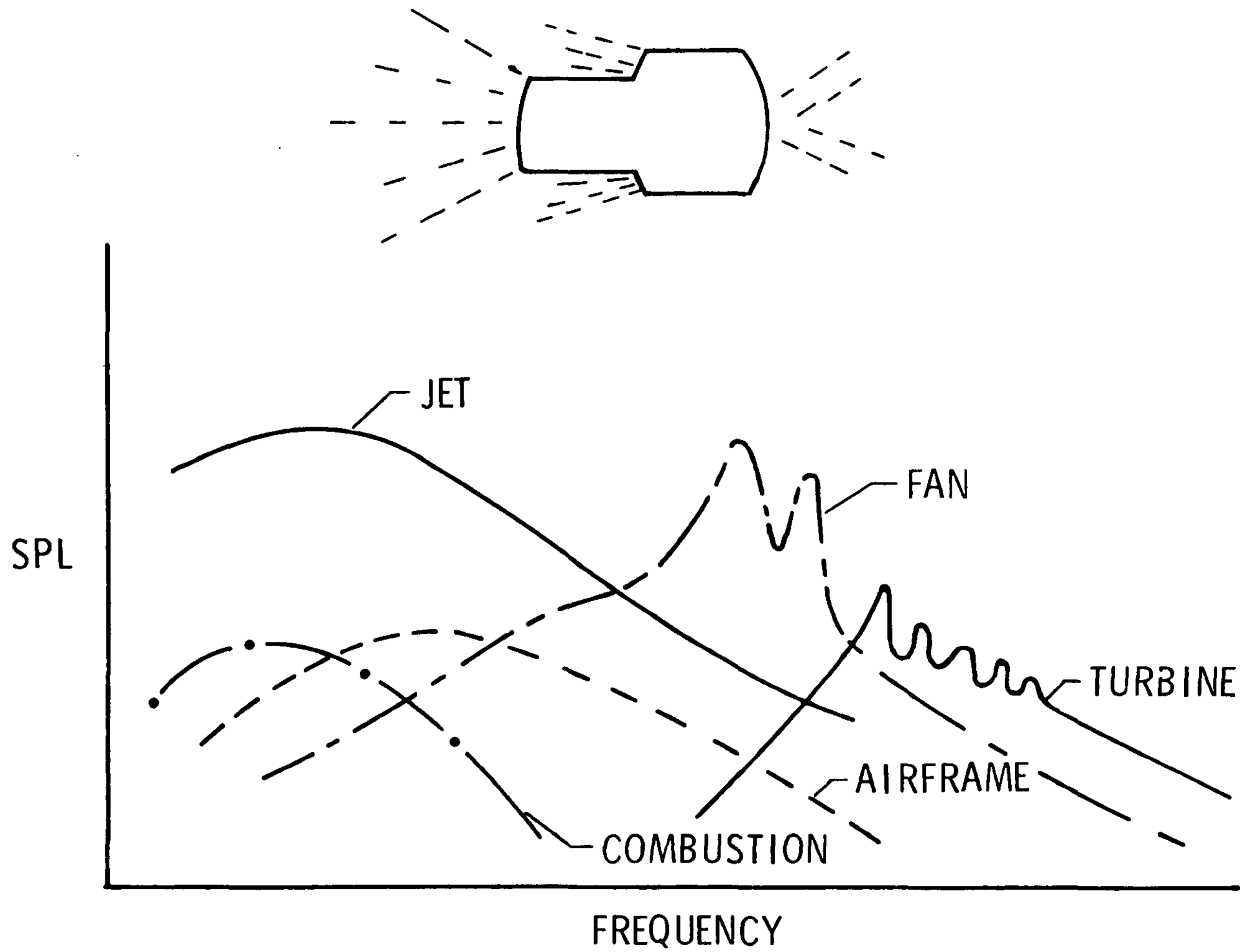


FIG. 2 TYPICAL SOURCE NOISE COMPONENTS.

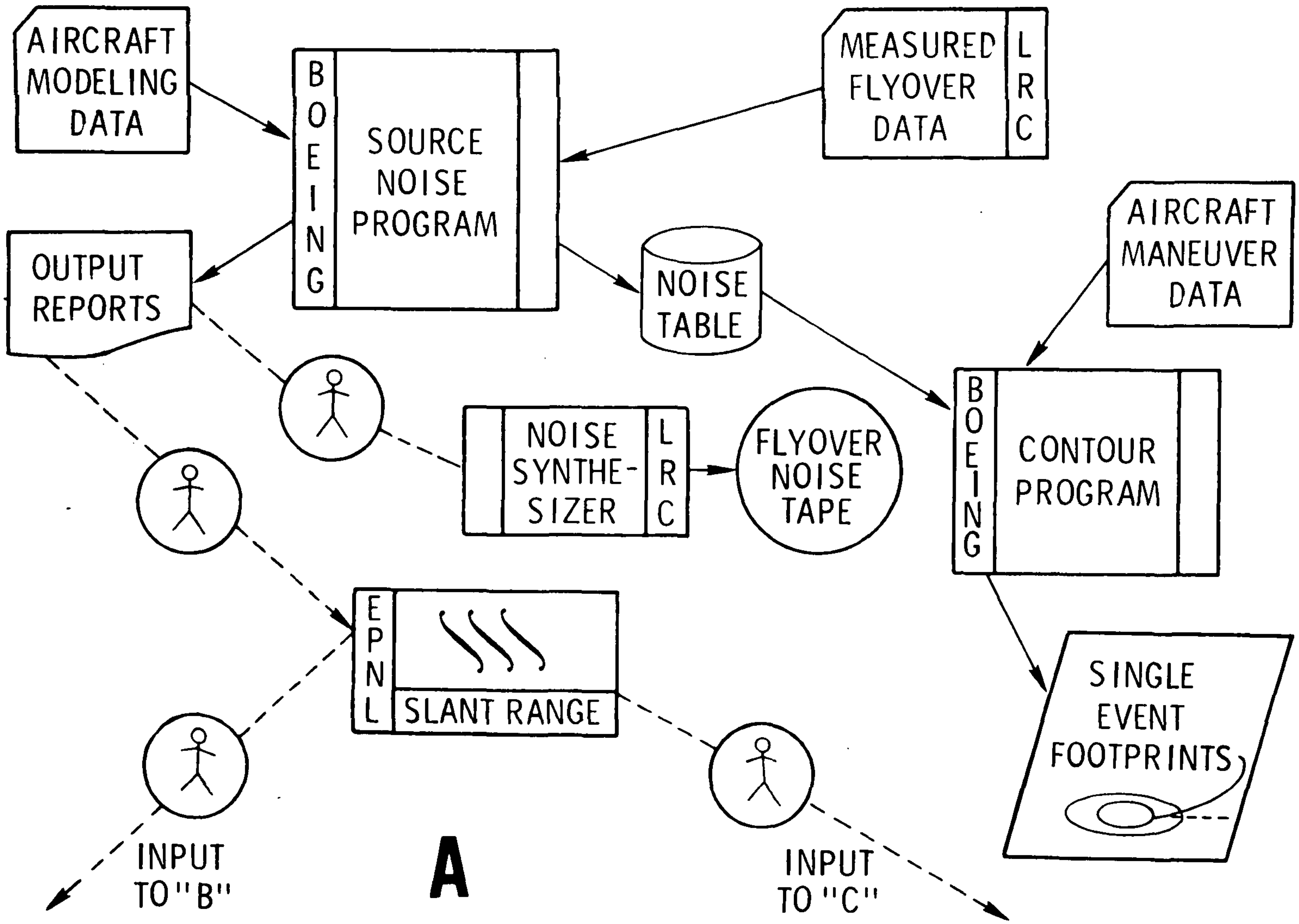


FIG. 3A INTERIM AIRCRAFT NOISE PREDICTION PROGRAM.

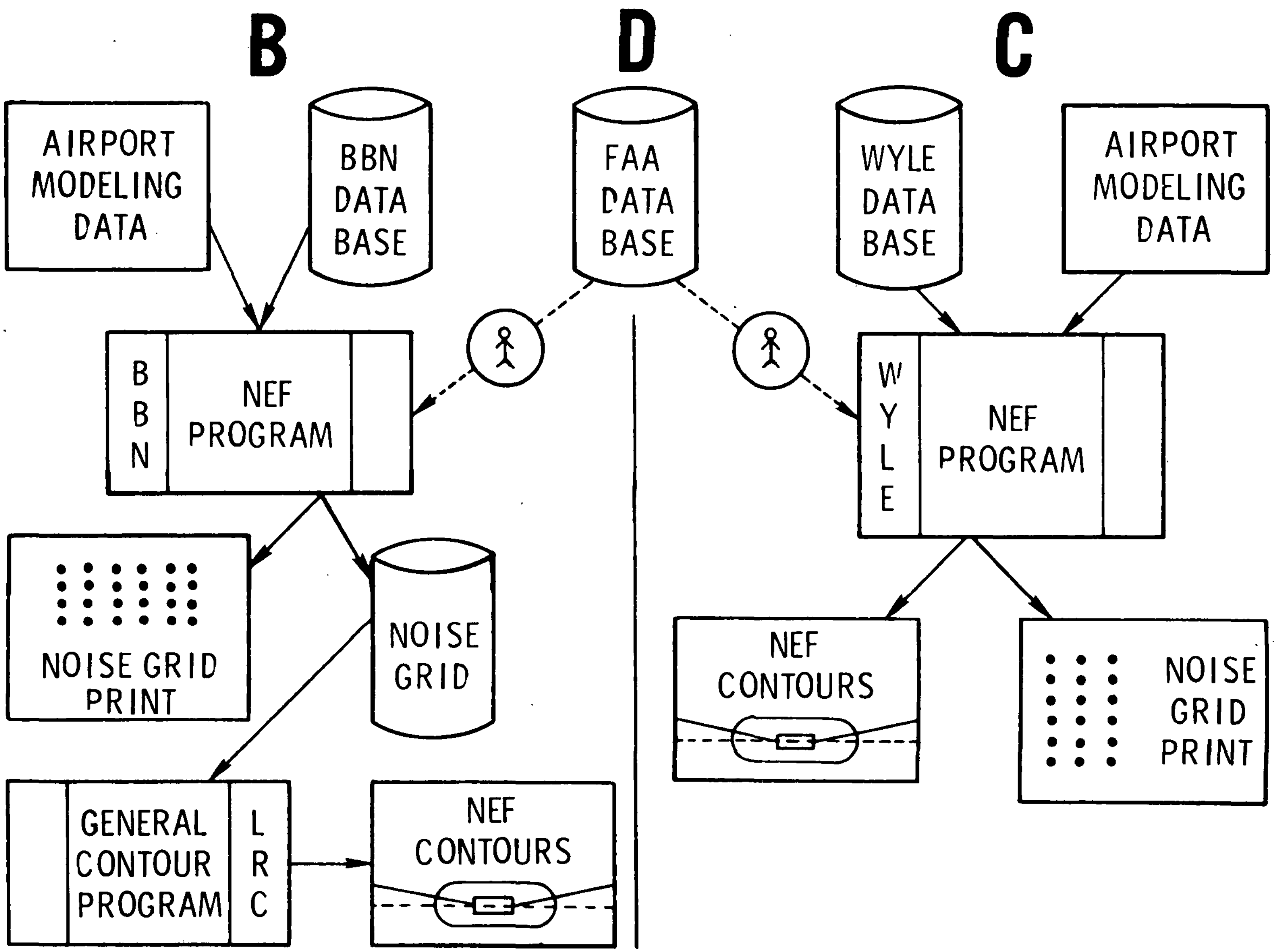


FIG. 3B INTERIM AIRCRAFT NOISE PREDICTION PROGRAM.

OPERATIONS AND MEASUREMENTS	AIRCRAFT OPERATIONS AND PERFORMANCE FLYOVER NOISE MEASUREMENT ENGINE TEST STAND MEASUREMENT
FLUID FLOW	ENGINE AEROTHERMODYNAMICS EXTERNAL AERODYNAMICS
FAN NOISE	SUBSONIC FAN NOISE SUPERSONIC FAN NOISE COMPRESSOR NOISE
CORE NOISE	COMBUSTION NOISE TURBINE NOISE
DUCT ACOUSTICS	TRANSMISSION THROUGH TURBOMACHINERY DUCT FLOW NOISE ACOUSTIC MATERIAL AND DUCT LINERS DUCT TRANSMISSION DUCT RADIATION
ROTOR NOISE	ROTOR NOISE PROPELLER NOISE

FIG. 4A KEY TECHNOLOGY TOPICS.

FLAP NOISE	OTW BLOWN FLAP NOISE UTW BLOWN FLAP NOISE
JET NOISE	CIRCULAR JETS NONCIRCULAR JETS JET SUPPRESSORS THRUST REVERSERS
AIRFRAME NOISE	AIRFOIL NOISE CAVITY NOISE LANDING GEAR NOISE AIRFRAME DRAG NOISE
SHIELDING	WING SHIELDING FUSELAGE SHIELDING FLOW SHIELDING
PROPAGATION	ATMOSPHERIC ABSORPTION ATMOSPHERIC REFRACTION EXCESS GROUND ATTENUATION TURBULENT SCATTERING

FIG. 4B KEY TECHNOLOGY TOPICS.

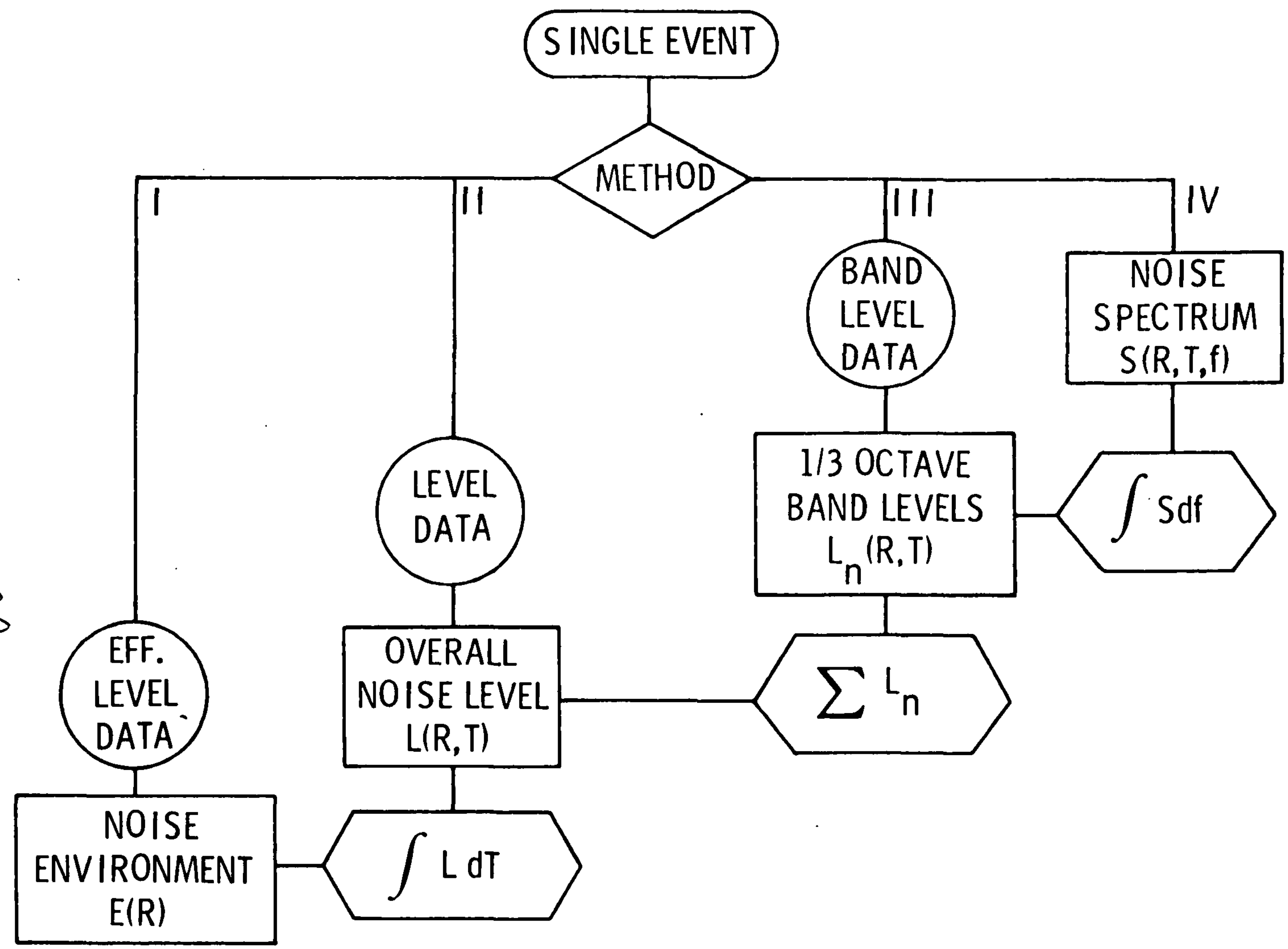
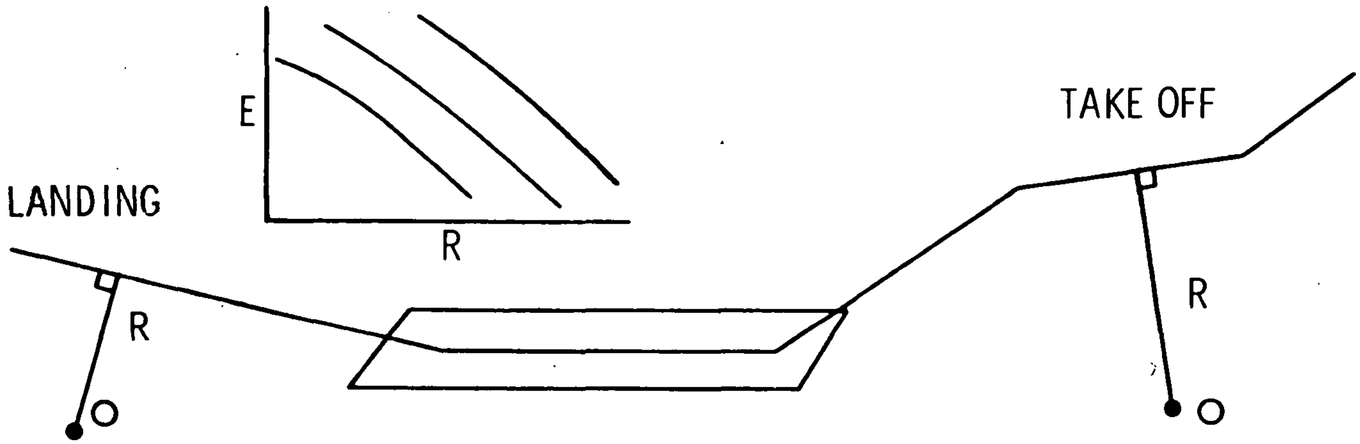


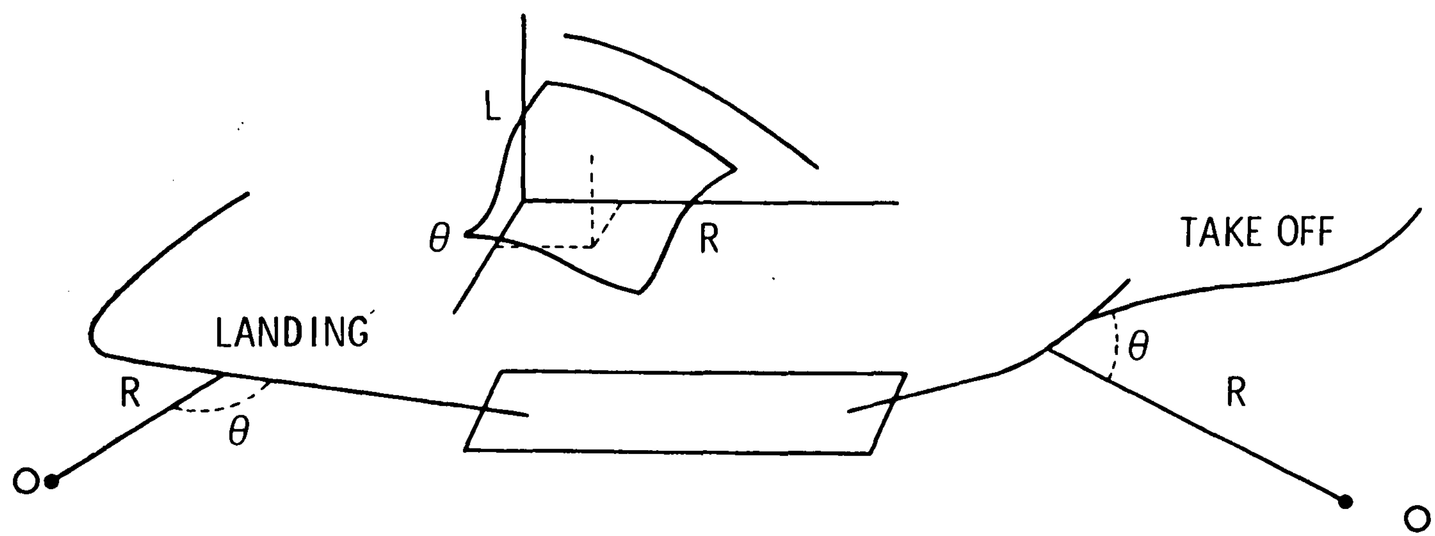
FIG. 5 ANOPP LOGICAL LEVELS.



- AIRCRAFT DATA BASE: EFFECTIVE NOISE LEVEL (EPNL, ETC.) VS SLANT RANGE
- STRAIGHT LINE SEGMENTS DESCRIBE AIRCRAFT OPERATIONS
- SUITABLE FOR ROUGH ESTIMATES OF COMMUNITY NOISE ENVIRONMENT
- MINIMAL KNOWLEDGE OF AIRCRAFT NOISE REQUIRED FOR USE

FIG. 6 ANOPP LEVEL I.

34



- AIRCRAFT DATA BASE: NOISE LEVEL (dBA, PNdB, ETC.) VS RANGE AND DIRECTIVITY
- SMOOTH, CURVING AIRCRAFT TRAJECTORY
- ESTIMATES TIME HISTORY OF AIRCRAFT NOISE LEVEL AND PROVIDES REFINED ESTIMATE OF COMMUNITY NOISE ENVIRONMENT
- GENERAL KNOWLEDGE OF ACOUSTICS AND AIRCRAFT NOISE REQUIRED FOR USE

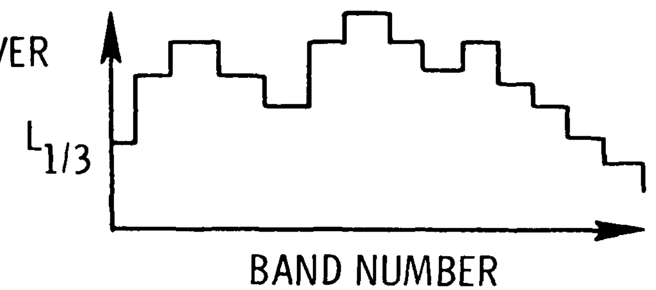
FIG. 7 ANOPP LEVEL II.

$\underbrace{\text{SOURCE NOISE} = \Sigma \text{ AIRCRAFT} + \text{JET} + \text{FAN} + \ldots}$

DIRECTED 1/3 OCTAVE BAND LEVELS

PROPAGATION

- COMPONENT DATA OR EMPIRICAL FORMULAS
- PREDICTS REAL-TIME SPECTRUM AT RECEIVER
- SUITABLE FOR AIRCRAFT/ENGINE SYSTEMS STUDIES
- IN-DEPTH KNOWLEDGE OF AIRCRAFT NOISE REQUIRED FOR USE



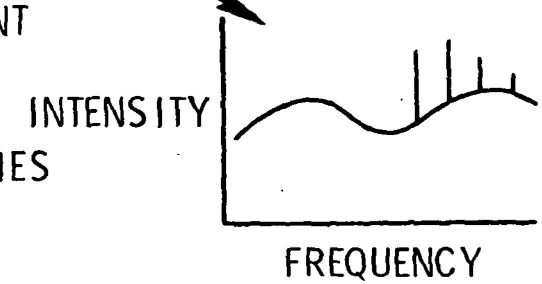
REAL-TIME SPECTRUM RECEIVED

FIG. 8 ANOPP LEVEL III.

$\underbrace{\text{SOURCE NOISE} = \Sigma \text{ AIRFRAME} + \text{JET} + \text{FAN} + \ldots}$

DIRECTED CONTINUOUS, DISCRETE SPECTRA

PROPAGATION



- ANALYTICAL MODELS OF NOISE SOURCE COMPONENT
- PREDICTS REAL-TIME RECEIVED SPECTRUM
- SUITABLE FOR DETAILED, ADVANCED DESIGN STUDIES
- FOR EXPERTS ONLY

FIG. 9 ANOPP LEVEL IV.

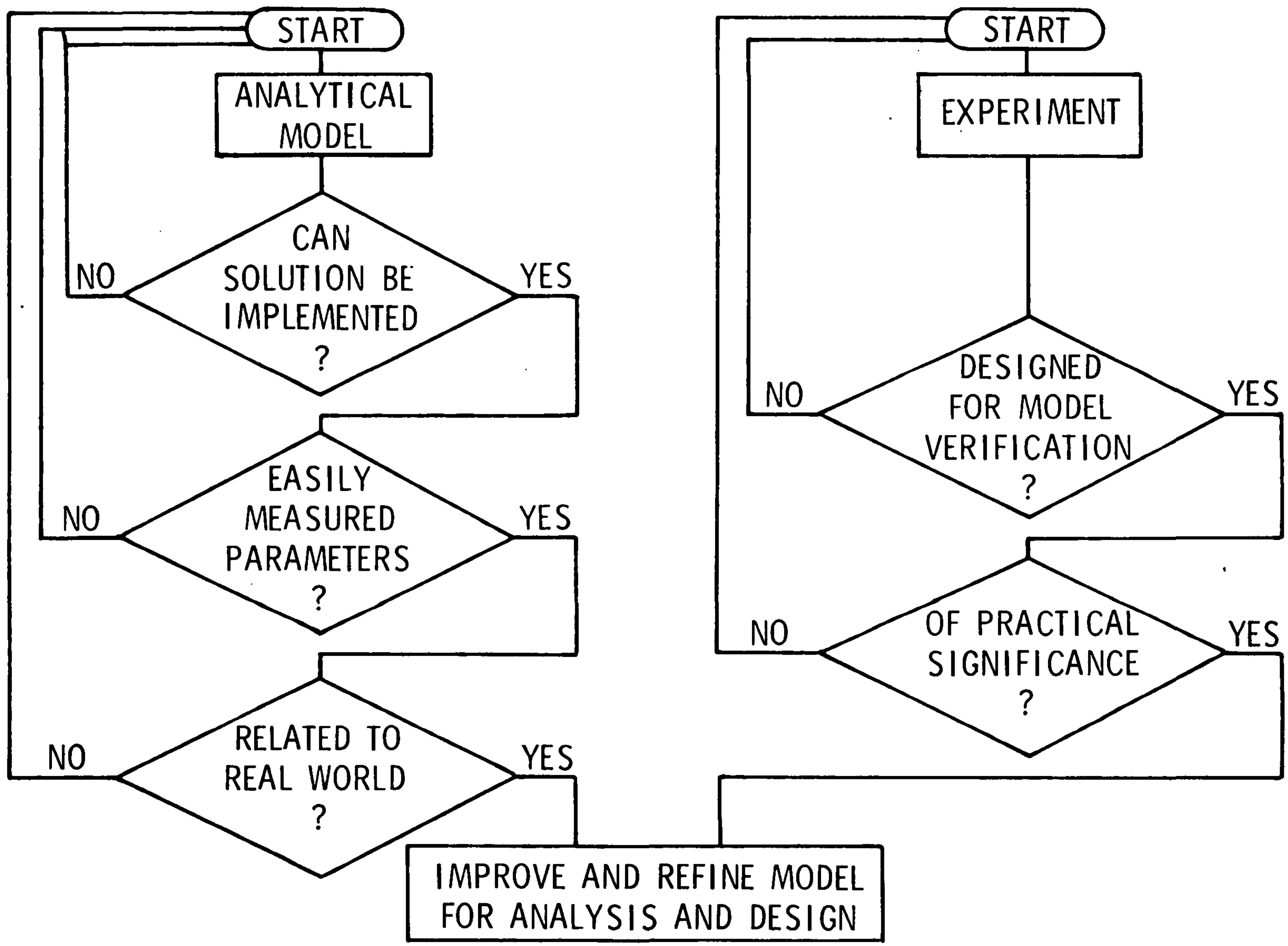


FIG. 10 ANALYTICAL MODEL GENERATION.