TECHNOLOGY UTILIZATION

ACOUSTICS TECHNOLOGY

A SURVEY

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ACOUSTICS TECHNOLOGY

A SURVEY

By

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1. Acoustics

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Foreword

The National Aeronautics and Space Administration (NASA) established its Technology Utilization Program to disseminate information on technological developments "which appear to be useful for general industrial applications." From NASA research centers, NASA contractors, and other sources, space-related technology is collected and screened, and that which has potential industrial use is made generally available. This survey is one of a series of NASA publications that include information of interest to the nonaerospace community.

In this survey, the major revival and expansion of acoustic technology that took place in the middle of this century has been reviewed. An extensive increase in basic knowledge, widespread experimental study, and public interest in the technology, together with a broader application of it in industry were realized during this period. The overall effort should lead, in a scientific sense, to the solution of such nonlinear problems as how the inherently nonlinear flow fields of aerodynamics act on the more typically linear motions of acoustics; and, in a social sense, to a determination of how cacophonous whines, roars, and bangs affect man, and how to deal with them.

The information in this document is based on a comprehensive examination of the literature available on the subject. The reference material is concerned primarily with investigations of the mechanisms by which noise is generated, the propagation of noise by spacecraft boosters, the origin of noise generated by compressors in aircraft turbojet engines, and the subjective effects of noise on humans. Because many of these investigations are still in progress, the extent to which they are treated is limited in some cases. It is hoped, however, that the information presented here will stimulate interest in acoustics and the control of noise, and will guide interested persons to sources of specific information in the literature presently available.

RONALD J. PHILIPS, Director
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Contents

CHAPTER 1

Introduction

The National Aeronautics and Space Administration (NASA) and its predecessor, the National Advisory Committee for Aeronautics (NACA), have demonstrated continuous interest in the problems of sound and acoustics, particularly those involving noise reduction. As early as 1916, for example, NACA issued a study of aircraft engine mufflers (ref. 1), and a report on the undesirable effects of aircraft engine noise appeared as early as 1928 (ref. 2), but it was the advent of the jet transport in the 1950's that first intensified NACA's concern with noise problems.

Following the establishment of NASA in 1958, progressively larger space boosters were tested and fired. The noise generated by these devices produced a new set of problems to solve. Still later, the introduction of supersonic aircraft added a further dimension to the general problems. As noted, interest has been centered in the undesirable aspects of sound. To both NACA and NASA sound has meant noise, very severe noise, which somehow had to be moderated. Solving noise problems has ranged from preventing human dissatisfaction and complaint to assessing means for avoiding either human injury or material damage caused by the noise of certain tests and processes.

A turbojet aircraft engine makes two kinds of noise. One is the external noise resulting from the turbulence generated by the encounter of a high-speed jet with the stagnant atmosphere; the other is high-intensity whining caused by the fast rotation of the engine's multi-bladed compressor. A rocket, on the other hand, produces just one primary source of sound—the turbulence caused by its exhaust impacting the surrounding atmosphere. The effects of such noise may be divided into two broad categories: effects on physical objects and effects on human beings. Structural damage to an aircraft can be caused by the noise field produced by its jet engines, and a spacecraft can suffer damage from the greater noise fields produced by its boosters. Possible damage to airport structures from aircraft engine noise, and to launch stands, instrumentation buildings, and other surrounding installations from space boosters, must also be considered. The effect of noise on human beings ranges from actual physical injury occurring from too close proximity to an aircraft engine, spacecraft test, or launch, to the psychological disturbance and annoyance incident to the noises generated.

The sonic boom generated in supersonic flight by aircraft creates a noise source of special significance. In a sonic boom, the structural and human response problems appear to be particularly closely related, since human beings are apparently affected by the manner in which the surrounding structures respond to the sonic boom.

NASA has made specific technical contributions primarily in four areas. Perhaps the most important area, and the one to which maximum effort has been applied, is determining what mechanism generates the noise from high-speed gas jets. The basic principles used for analyzing this phenomenon were fairly well established in the mid-50's, primarily from theoretical work performed in England during that period. However, NASA has accumulated much objective data regarding factors affecting the amount of such noise, the means of measuring it, and methods of predicting the noise that may be produced by jet engines of future spacecraft.

Another area of NASA concentration is the study of noise propagated by spacecraft boosters in the atmosphere. If, for any reason, noise propagation follows an anomalous path in the atmosphere, it may not diminish rapidly, and may cause disturbance, or even damage, at a considerable distance (on the order of tens of miles). It is possible, however, to predict the conditions under which anomalous propagation will occur. This will permit launchings or tests to be scheduled when the atmospheric conditions are favorable, so that the deleterious effects of such noise can be reduced, or even avoided.

A third area of NASA activity is investigating the origin of the compressor noise generated in a turbojet aircraft engine. Emphasis on such studies has increased with the growing popularity of the turbofan type of engine, which produces a proportionately larger amount of compressor noise than earlier models of the turbojet.

The last major field of NASA concentration, and the one that may be of the greatest long-range nonaerospace value, is determining and evaluating the actual subjective effects of noise on human beings. Previous efforts to measure objectively the actual noisiness of the sound, that is, its capacity to disturb the human being, are not truly correlated with the subjective effects, and have led to the development of means to suppress certain aspects of the sound that are not sources of disturbance to individuals. The development of a more valid measurement of the subjective effects of noise may turn out to be the most useful tool of all.

The scope of this survey is necessarily limited because many of the investigations outlined above are still in progress. Masses of data will continue to be generated for analysis, and intensified efforts will be needed to interpret current investigative results. NASA's work in acoustics at any point in time presents a complex picture. This is inherent in the analysis of many modern industrial processes, because the logic of the activity is clearly apparent only when the investigation is completed and the results are presented in an organized manner. In some situations, a progress report on an unfinished investigation may be useful, but in others, it may be very confusing and inconclusive. This survey contains material selected on the basis of the author's best judgment. The objective criteria upon which these selections are based are briefly noted in the succeeding discussions.

Investigations of perceived noise become more important as the world develops a greater awareness that sound is one of the atmospheric pollutants. The establishment of a criterion by which certain sounds in this pollution can be evaluated, and by which different sounds can be distinguished from each other, appears to be a desirable and useful effort. The fact that aerospace vehicles generate new and unusual sources of excessive noise indicates that an objective criterion for determining various levels and characteristics of noise over a broad spectrum will be both technically and legally necessary in the future.

The theory of sound generation by jet turbulence will be discussed only briefly in this survey for several reasons. In the first place, an adequate understanding of the means to predict sound levels produced by relatively small jets employed in industrial processes is currently available. NASA has not made any major contributions to the understanding of jet noise of this kind because the agency deals with noise of greater magnitude than that encountered in industry. Since NASA investigations of jet noise are still in progress and do not yet indicate any significant patterns, literature on the subject from NASA and related sources is relatively incomplete. In addition, many of the highly technical data are still controversial, because many of the mechanisms of sound generation are not yet understood. Undoubtedly this area of investigation will be properly covered by a specialist in the field at some future date. Consequently, noise generated from turbulence will be only briefly outlined here. A relatively large number of references are cited, however, for the technically oriented reader who wishes to examine the subject more extensively.

The sonic boom clearly has some relevance to the building industry, because shock-resistant structures are needed in areas that may be exposed to the destructive effects of this type of noise, but the effects of sonic-boom noise will be covered only briefly in this survey. The process by which shock waves are created at the aircraft or other device moving faster than the velocity of sound is an aspect of broader interest in sonic-boom investigation. Such shock waves can be encountered in industrial processes where gases move at supersonic speeds. Consequently, the mechanism that generates the boom, as distinguished from its propagation, has a potentially wider application to nonaerospace enterprises, and will, therefore, be covered in greater detail.

The principal approaches in dealing with the loud noises generated by rocket boosters are (1) suppressing the noise, and (2) predicting whether or not the noise of a given test or launch will cause disturbance. This effort involves the actual suppression of noise by a mechanical or acousto-mechanical device, or predicting the long-range propagation of such noise, or both. Considerable interest was shown in various forms of sound suppressors, primarily liquids, until the first large-scale Saturn test had been performed. It was discovered that sound levels produced by such tests were reasonably predictable; consequently, interest in suppressors was reduced. The developed principles of suppression, however, may have application in the nonaerospace sector and will be discussed at some length.

Although NASA has performed significant studies in the prediction of the long-range atmospheric propagation of high-level sound, the material is omitted because of its extreme complexity. While it is impracticable to predict the actual point at which sound waves traveling through the atmosphere by anomalous propagation will be focused, it is now possible to predict the probability that some sound waves of this sort will reach the ground. For example, given a multi-layered atmosphere similar to that of the southeastern United States at the Mississippi Test Facility and at Marshall Space Flight Center, where temperature inversions may be found, means have been devised to make detailed measurements of the atmospheric conditions, and on the basis of these data, to make relatively rapid predictions of the probability that some sound waves generated by large booster tests will return to the ground.

Jet noise suppressors of the type used on turbojet and turbofan aircraft engines will be discussed in some detail, because these devices may have application to industrial processes in which turbulent noise may be generated. NASA research on compressor noise that is encountered in the turbojet aircraft engine, for example, has such application, because axial-flow compressors are now used extensively in American industry.

In preparing this survey, a large amount of information was examined. Much of this information is not discussed in detail in the text, but is included as organized reference material. The number of references, however, is not necessarily indicative of the importance of any particular topic. The objective is to guide interested persons to more information on the various subjects involved, and to give some advice on sources of information not directly or easily accessible. Only those portions of NASA's research in acoustics which have direct or indirect application to the nonaerospace industry, regardless of their level of coverage, are included in the scope of this survey.

CHAPTER 2

Noise Generation

TYPES OF NOISE

Aside from the explosive sound of the sudden shock wave of the sonic boom, NASA is primarily concerned with the rather broad-band noise generated by various forms of gas turbulence. This has been described as aerodynamically generated noise. Classic research in the mechanics of aerodynamic noise generation was accomplished by Lighthill in England in the 1950's, and more recently by Ffowcs-Williams (refs. 3, 4, and 5). At present, the basic mechanisms of noise generation are probably understood theoretically, and variable phenomena of noise under certain conditions can be predicted; but many of the multiplying factors are still obtained arbitrarily or empirically, and thus no direct solutions of basic equations exist.

The turbulence that generates broad-band noise can be created in two ways: by the interaction of a high-speed jet of gas with a relatively motionless gaseous surround, and by fast relative motion of a solid object, such as an aircraft or space vehicle, in the atmosphere. The first mechanism of noise generation may be called jet-turbulence noise, and the second, boundary-layer noise. The boundary layer is a region, between the moving physical object and the gaseous medium through which it moves, where turbulence is generated. It is here that the mechanisms of the noise generation must be studied.

In the generation of jet-turbulence noise, there are significant differences between the actions of supersonic and subsonic jets. When the jet velocity is supersonic, weak shock waves (Mach waves) are created by turbulent eddies in the interaction region. The Mach waves propagate at approximately the jet-exit velocity at the Mach angle (angle whose cosine is M^{-1}, where M is the Mach number) relative to the main stream. The angle varies for a given jet because the speed of the individual eddies varies. When the jet is subsonic, the methods of Lighthill and others give a fairly precise picture of the generation process. Primarily, their studies indicate that the turbulent areas act as sonic quadrupoles. Because they are quadrupoles, their directional pattern is lobed and the intensity of the generated sound is related to the eighth power of the jet velocity. The basic mechanism of sonic generation follows this pattern fairly well, but in any specific jet system, there may be a variation from the usual pattern and some dipole noise sources will be observed. For supersonic jets the relationship with the mean jet velocity gradually changes to a third power law—but with a much bigger multiplying factor.

Characteristic of jet-turbulence noise generation, the noise spectrum, although broad and almost white, tends to peak towards lower and lower frequencies as the scale of the noise generator is increased (for example, increase in the size of rocket boosters). Current analysis of fundamental turbulence does not completely explain this phenomenon. One hypothesis advanced has been that, because the majority of very large jets are created by burning fuel, combustion within the jet itself adds this low-frequency component. However, some of this shift to lower frequencies can be observed even in cold jets that are created by so-called "blowdown" jet noise generators. The question is not currently resolved.

The basic mechanism of noise generation through turbulence is complicated because the physical form of the noise generator affects the actual noise output. For example, the jet stream is typically deflected to one side in a test stand for rockets. This deflection affects the propagation pattern and the spectral distribution of noise energy. In addition, rocket clustering leads to complex interference effects and consequent changes in the character of noise.

Describing jet-generated noise in detail is difficult, because the jet is a source of extended noise; that is, the noise seems to originate from a long section of the exhaust plume. The overall propagation pattern of the noise, therefore, is very complex. In acoustic studies, the near field and the far field are areas of the propagation pattern in which quasi-wave propagation and true wave propagation take place, respectively. The large and extended noise sources of turbulent jets seem to have an additional field, the geometric near field, in which the actual shape of the jet affects the point-to-point intensity level of the sound. There are other secondary fields of sound propagation that interact with the primary fields discussed above. One of these, for example, is a type of near field, called the induction field, in which actual wave propagation does not occur, but differences in pressure that eventually propagate sound can be detected. In assembling data to determine the intensity of a given jet noise source, distinguishing among these fields often becomes extremely important. For studies of rocket noise, sound measurements in the near field are useful to determine sources of sound generation. In the far field, most of the undesirable effects of the sound occur.

Dealing with the acoustic fields indicated above constitutes a serious problem in the space program. An intense near field completely surrounds a spacecraft before it leaves its launching pad, and a similar condition exists with a jet aircraft while it is being static-tested. The engine noise in the near field may damage the structure of the vehicle in each case. In determining the intensity of acoustic stress to which a particular part of the equipment is subjected, an accurate evaluation of both the induction field and the geometric near field is important. In establishing the vulnerability of buildings in the immediate vicinity of the noise, and of people located at even long distances from the actual test or launch, the far-field pattern is the important factor to consider. Because the noise is generated at an extremely high intensity, such problems as locating the joint at which conventional linear sound transmission begins, determining where the gas compression is adiabatic, and the like, are extremely difficult.

Knowledge of the mechanism of jet noise generation is fundamental to the solution of problems of noise reduction and suppression. It is necessary to understand the generating mechanism to reduce noise at its source, or to suppress it by some sort of a muffler. Reduction of jet aircraft noise has been extensively studied by NASA researchers, but relatively little rocket-noise suppression has been attempted. In nonaerospace applications, suppression may be an extremely important activity.

Boundary-layer noise constitutes a considerable portion of the total noise generated by aircraft flying at subsonic and supersonic speeds, and can cause damage to aircraft at such speeds. A spacecraft moves relatively slowly in the dense lower atmosphere, increases its speed as the atmosphere becomes thinner, and, at a certain point, becomes vulnerable to more damage from noise and vibration generated by boundary-layer effects than any other influence. On the initial Mercury flight, this effect produced a surprisingly greater vehicle stress than that occurring at lift-off. This effect is sometimes referred to as high altitude buffeting or, in the astronautical terminology, "high Q," and was a matter of concern to aeronautical engineers long before the development of aircraft whose speeds could create boundary-layer noise. Phenomena of this sort occur when the velocity of propellers or helicopters' rotors through the atmosphere exceeds that of the aircraft itself.

Before the establishment of NASA, a large backlog of studies on boundary-layer noise generation was developed by its predecessor agency, NACA. The reduction of boundary-layer noise of aircraft and conventional spacecraft moving through reasonably dense atmospheres has been accomplished by improving or modifying the surface quality of the vehicle. The effects of surface characteristics of aerospace vehicles, such as projections or depressions, surface polish, texture, and other surface features, have been studied extensively. In the case of very large objects, particularly spacecraft, the coupling between the fluctuating energy generated at the boundary layer and the panels forming the outside skin of the vehicle can cause damaging effects. Extensive study of this coupling process has been conducted to find ways to reduce its effects on the panels by damping or similar means. In addition, the propagation of such generated noise into the vehicle itself has been studied.

The sonic boom, a major source of noise that is fundamentally different from the turbulent gas sources treated so far in this discussion, has also been exhaustively researched by NASA in its role as a support arm to government agencies. Studies of sonic-boom noise as it relates to nonaerospace applications are discussed later in this survey.

Another important form of noise not directly related to aerodynamic noise or the sonic boom is the noise generated by compressors of jet-powered vehicles. The basic compressor noise appears to originate in a mechanism comparable to a siren in which a series of vanes cut a moving stream of gas and produce intermittent regions of intense gas pressure and velocity. Although compressor noise in jet aircraft was not originally important, the introduction of the fan-jet aircraft and success in reducing some of the actual jet-turbulence noise intensified interest in compressor noises. It has been recently demonstrated that the fixed-pitch noise from a compressor is more unpleasant than an equivalent amount of noise from turbulence.

The primary difference between industrial and NASA research in sources of noise and its generation is that industry generally deals with noises of lesser magnitude than those of interest to NASA. Admittedly, in some industrial situations devices are used that will generate noise equivalent to that produced by the massive noise makers employed by NASA, but this is not generally true. Most of the sources of noise considered in this survey, however, will have counterparts in some form in domestic industry. Many turbulent high-speed gas flows, for example, including those in which combustion takes place, are found in industrial processes.

These occur in such ordinary devices as the gas furnace or oil burner in the home.

The noise sources discussed above have been studied extensively by researchers associated with the NASA program. The information derived from these studies has been documented in NASA reports, such as this survey, for the purpose of developing a better understanding of noise phenomena throughout the scientific and industrial communities. In this way the technology of acoustics and its related fields can be advanced. Although such effects as spectrum anomalies of sound generated by turbulence from massive jets may now have apparent value to a specific industrial process, the analysis of the phenomenon may indeed lead to very useful industrial applications. The effects of boundary-layer turbulence are observed not only with spacecraft and aircraft moving at high speed through the atmosphere, but also with high-speed flow of fluids or gases in pipes. Admittedly, the sounds surrounding industrial devices may not be as intense as those generated by a spacecraft at lift-off, but the knowledge of vibration and its capacity to damage structures that can be acquired from studies of boundary-layer phenomena can be useful in developing measures to protect industrial equipment from the damaging effects of noise and vibration.

Useful industrial applications of the sonic-boom phenomena, however, are not readily apparent. There will undoubtedly be some interest in the effects of sonic booms on structures that will stimulate the development of building materials and structural designs resistant to these effects. Researchers in NASA and other investigators have studied the phenomena of initiation and propagation of sonic shock waves that cause sonic booms. These investigations have been conducted on both microscopic and macroscopic scales.

Subsequent discussions in this survey deal with the several noise sources defined above, based on the research that has been indicated in each case.

NOISE GENERATED BY TURBULENCE

In 1960, Howes of Lewis Research Center investigated a specific characteristic of jets which is important in understanding the noise output of a subsonic jet (ref. 6). He proposed that radiated acoustic power of this sort is related to the strengths of noise sources that are distributed along the jet. This hypothesis had been well established previously in theory by other investigators, but had not been confirmed experimentally.

On the other hand, pressure fluctuations along the mean-velocity boundary of a jet had been measured, but no attempt had been made to predict theoretically the shape of their distribution. Based on a mathematical analysis analogous to the methods used by Lighthill in his classic studies (refs. 3 and 4) and on a few experimental measurements, Howes found that the shape of the pressure-fluctuation distribution was generally in accord with the theory of near-field pressure fluctuations in incompressible fluids. He observed, however, that jet temperature, which is not considered in the theory, affects the values of the fluctuations and their distribution, especially near the nozzle. Larger pressure fluctuations occurred as the temperature of the jet was elevated. Furthermore, the jet-nozzle geometry also affected the fluctuating-pressure distribution, especially near the nozzle, by introducing a nonuniform exit-velocity distribution.

In 1964, Ffowcs-Williams, in his research under contract for NASA, made major contributions to the theory of turbulent aerodynamic noise generation (ref. 7). His studies had to do specifically with the mechanism of noise generated by supersonic flows. The new information resulting from these studies was limited in depth, however, because experimental data on the near-field noise generated by supersonic jets was lacking. Keast and Maidanik performed some of the experimental work needed in 1966. Their work is reported in reference 8. The results of the research described in these two reports are of considerable importance and will be referred to in subsequent discussions in this survey.

Phillips' theory of noise generation in supersonic flows is based on the assumption that Mach waves generated by eddies within the flow produce the entire acoustic field (ref. 9). This theory represents an abandonment of Lighthill's acoustic-analogy approach (refs. 3 and 4), which involved the insertion of flow parameters into the turbulent-stress tensor; a tensor that could not be determined until the problem was fully solved. In effect, the new theory postulates that the only information needed to understand an acoustic field is knowledge of mean-flow gradients, temperature changes (to include effects of refraction), and the turbulent-velocity field. This new approach, although controversial, appeared to be a more useful tool for further analysis than the circular and, therefore, inaccessible method of Lighthill. Unfortunately, fundamental errors have subsequently been observed in Phillips' formal solution, and the validity of the results is now questioned. This, however, does not detract in any way from the basic usefulness of his approach.

Ffowcs-Williams reports three major theoretical improvements on the work of previous investigators. The first is an approach that combines the theories of Phillips and Lighthill, and demands only a knowledge of eddy-convection velocity, rather than mean-flow velocity and pressure fluctuation at the eddies. The second is a theory that eddies in the flow generate intense sound as they decelerate, a process that must occur continuously after they are formed. The decelerating eddies radiate strongly along the Mach angle as a result of changes in their convection speed. Since this speed in a rocket exhaust varies between the speed of sound and half the nozzle exit speed, the Mach angle has a rather wide range of possible values. Consequently, the actual radiating angle is widely spread. The third important point made is that a sufficient understanding of the radiation of Mach-wave sound that occurs in supersonic shear flow in rocket exhausts makes possible a detailed comparison of theory and experiment. The Ffowcs-Williams report closes with the suggestion that a suitable experimental program logically would be the next step to take.

The report on the experimental program carried out by Keast and Maidanik is somewhat inconclusive. Although the stated objectives of the contract were achieved, some of the correlation procedures essential to the program were not completed because proper experimental conditions were not established. In general, the basic ideas suggested by Ffowcs-Williams were confirmed. The analytic part of the report describes in some detail the theory on which the correlation methods were based. In effect, it proposes that near-field sound measurements made on a supersonic jet are useful indicators of the nature of the turbulence within the jet. Comprehensive near-field measurements, therefore, should provide information with which the validity of the theoretical assumptions can be determined, and will be an effective tool for assembling data on the aerodynamics of sound-protection processes.

M. V. Lawson of Wyle Laboratories has investigated sound fields as they relate to motion (ref. 10). His thesis is in accord with that of Ffowcs-Williams but he approached the problem from a different viewpoint. He examined the sound fields generated by acceleration of propellers and helicopter rotors rather than those produced by deceleration of jets. For over a century it has been known that motion has an important effect on sound generation. The well-known Doppler effect on frequency was first demonstrated in 1842, and, more recently, the prediction of the effects of source convection formed an important part of the work of Lighthill (ref. 3). In Lighthill's paper and in studies of other investigators, attention has been focused on source convection at constant velocity. For example, Lighthill expressed the sound field for a point source in uniform rectilinear motion in such terms that, if the source were constant, no sound would be radiated. This is true for the uniform motion of a constant force in a straight line, but the convection of constant forces can indeed give rise to radiated sound. The sound generated by a propeller's thrust is a case in point. Consequently, Lighthill's restrictive assumption removed from consideration some of the factors related to radiated sound. Acceleration effects, which would be removed from the equation by a restriction to the case of constant velocity, are probably quite important. Centrifugal acceleration, for example, is involved in the noise generated by propeller thrust. Further, the effect of shock waves generated by an accelerating system suggests the possibility of a parallel acoustic case.

The object of Lawson's study was to derive the equations of the sound fields for singularities in motion under less restrictive assumptions, and to investigate some of the additional effects that appear. The sound fields for extended distribution of acoustic sources may be readily obtained by integration, and the evaluation of the integrals will depend critically on the retarded-time differences occurring within each source distribution. However, when the source is small compared with the typical wavelength of the sound generated, the retarded-time differences are small and the source may again be reduced for calculation purposes to an acoustic-point singularity.

In Lawson's experiments, the sound fields for a point source in arbitrary motion were first established and the effects of acceleration were determined. The results were used to calculate the sound radiation from a propeller and also from general rotary systems. A dimensional analysis was used to obtain a preliminary estimate of the relative magnitudes of the sound generated during uniform and accelerated motion, which indicated that acceleration effects will generally become more important at higher velocity. Finally, the results for both simple point sources and for point acoustic stresses in motion were found. The effect of arbitrary motion on the sound radiation of a simple source was readily understood, but only a preliminary interpretation of the result for acoustic stress could be made.

A theoretical analysis of the propagation characteristics of a finite amplitude pressure wave was prepared for NASA by Peter and Cottrell (ref. 11). The work was primarily concerned with the contribution of entropy-producing regions to the mechanism that generates aerodynamic noise. A mathematical model was formulated and analyzed for specific cases, one of which was determining the noise-generation characteristics of supersonic nozzles.

The approach taken by the investigators was based upon a simple basic idea, the essence of which is the choice of independent thermodynamic variables that will depict non-isentropic pressure fluctuations. Shock waves are generated at points where, in turbulent noise, irreversible (entropy-producing) events occur. The investigation considered the manner in which the waves generated at these entropy-producing starting points are propagated with a definable velocity. It was found that this velocity of propagation would approach the classical sound propagation velocity as the entropy produced varies toward zero. The triggering mechanism causing the entropy-producing events was examined. This led to the design of an extended plug nozzle for a jet exhaust which would facilitate the attenuation of noise by modifying the entropy-producing regions. The authors concluded that, for the specific cases investigated, the test data correlated satisfactorily with the theoretical results.

ROCKET AND JET NOISE

Mayes, Lanford, and Hubbard (ref. 12) have investigated ways of measuring noise fields of rockets, and of predicting the noise fields of rockets that are either untested or not yet constructed. Their study contains general information about the shape of the noise fields and the recurring pattern of rocket-produced noise. Solid-fuel rocket engines of 1500- and 5000-lb thrusts, which were designed primarily for jet-assisted-takeoff (JATO) aircraft operation, were examined. The nozzle-exit pressure of the engines was changed systematically to determine its effect on the noise level and spectra. The experiment revealed that the effect of nozzle pressure was not extreme, and made available also a wide range of data concerning the shape of the sound fields. The acoustic power radiated from the engines averaged about 0.5% of the mechanical power of the exhaust stream, a figure that is not consistent with the results of other studies. This problem of acoustic efficiency, therefore, is one of continuing importance because of its unpredictability. For large boosters, which are NASA's main concern, the acoustic efficiency follows a fairly smooth trend, so that noise fields for future rockets can be predicted with reasonable accuracy. For the nonaerospace user of much smaller rocket engines, the acoustic efficiency, and hence the noise prediction, is more uncertain.

Detailed noise-measurement surveys were made of six different nozzle configurations, five of which were designed to vary the exit-flow conditions sharply, and the sixth, for fixed exit flows. One of the five variable-flow configurations was a cluster arrangement, and the others consisted of expansion nozzles of the same input but of different exit diameters. Measurements of exit pressures in three tests of the fixed nozzles were greater than atmospheric; in two others, the pressures were approximately atmospheric; and in one test, the pressure was less than atmospheric. Figure 1 illustrates the mechanical relationships of the measuring procedure.

Figure 2 shows contours of near-field sound pressure levels (SPLs) of the rocket engine which was used with fixed-flow conditions for detailed noise surveys. The plot for the overall frequency range indicates, from the shape of the contours, that the noise originates approximately 20-nozzle diameters downstream of the jet exit. Polar plots in the horizontal plane of sound levels in the 250-Hz band and the 2500-Hz band, as well as the overall sound level, are shown in figure 3. Although these plots are based on tests for rocket engines with greater than atmospheric exit pressure, they are characteristic of the patterns of other nozzle configurations.

The power spectra of five of the tests are presented in figure 4 in terms of power spectrum level versus frequency. A generalization of these data is illustrated in figure 5, in which the sound power level is plotted against the dimensionless frequency parameter. The dimensionless frequency parameter comprises the diameter of the exit nozzle and the calculated exit-gas velocity as the

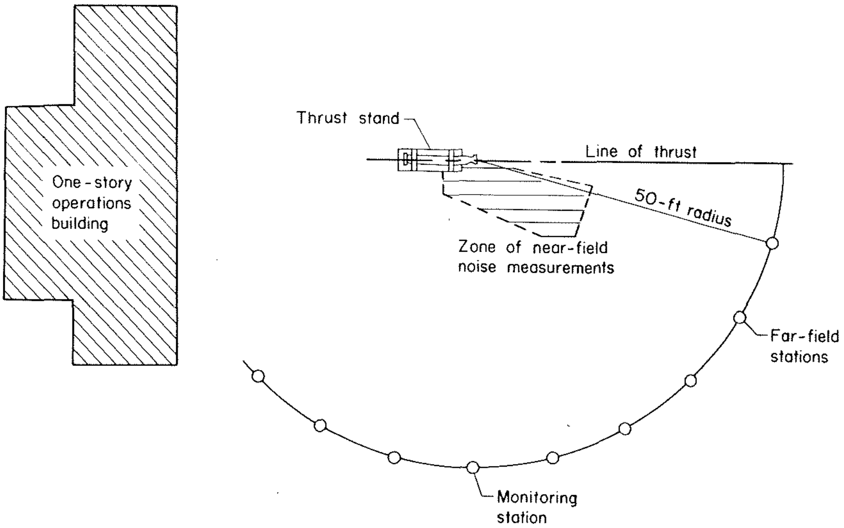


FIGURE 1.—Plan view sketch of test area, showing measurement stations for rocket-engine noise surveys.

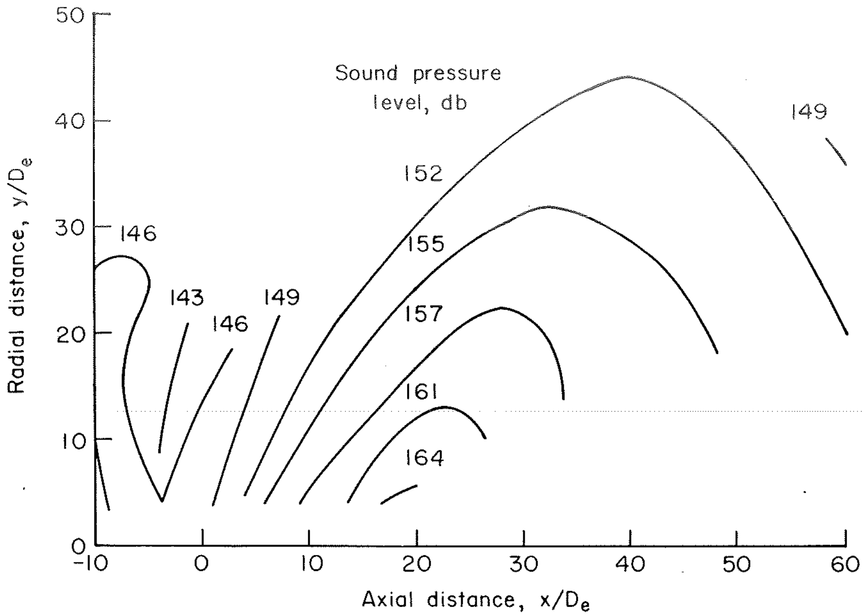


FIGURE 2.—Sound pressure level contours for typical solid-fuel rocket plotted against distances normalized for throat diameter.

scaling factor (Strouhal number). The use of the scaling factor appears clearly justified, since the sound-pressure curves fall into a very narrow range and correspond to data obtained by others from noise measurements of rockets as well as turbojet aircraft engines.

The investigators give a general description of energy distribution, in both frequency and space, of the turbulence noise generated in a simple rocket. Admittedly, the expressions for acoustic-efficiency trends and other numerical data do not appear to agree completely with those indicated in studies by other researchers. This inconsistency, still under study, is not conclusively resolved, which is understandable since turbulence noise is difficult to measure. However, the data should have general applicability in the nonaerospace industrial field.

NASA's studies of the noise made by jet aircraft engines usually relate to either the near field or the far field. The near field is significant since it has to do with the noise effects produced by a jet on the aircraft itself, including structural damage and generation of noise inside the aircraft. It is also of primary interest in studying the nature of the jet itself. Also of interest is determining how a given amount of jet-created noise affects the aircraft in the near

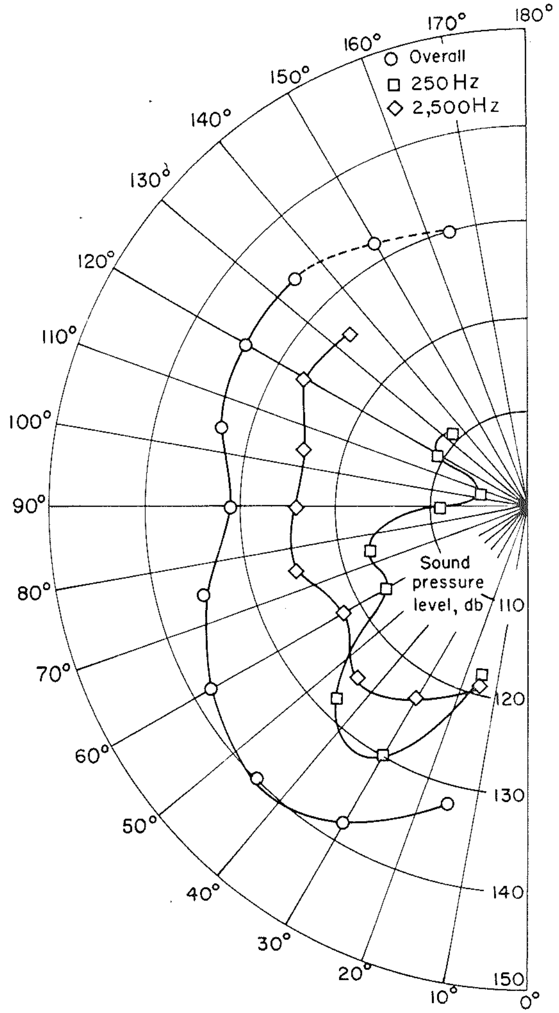


Figure 3.—Polar diagram of sound pressure levels measured at 50 ft in three frequency bands for a typical solid-fuel rocket.

field of the jet, if the jet moves at varying speeds. This aspect of research may have some indirect nonaerospace application.

Fakan and Mull of Lewis Research Center have reported an experiment in which near-field noise effects of a moving jet were observed (ref. 13). A wind-screened microphone was mounted on the aircraft at two- and three-nozzle diameters downstream of the exit nozzle of the jet engine. The aircraft was flown in level flight and trimmed. Then the engine was cut back to idling power. After

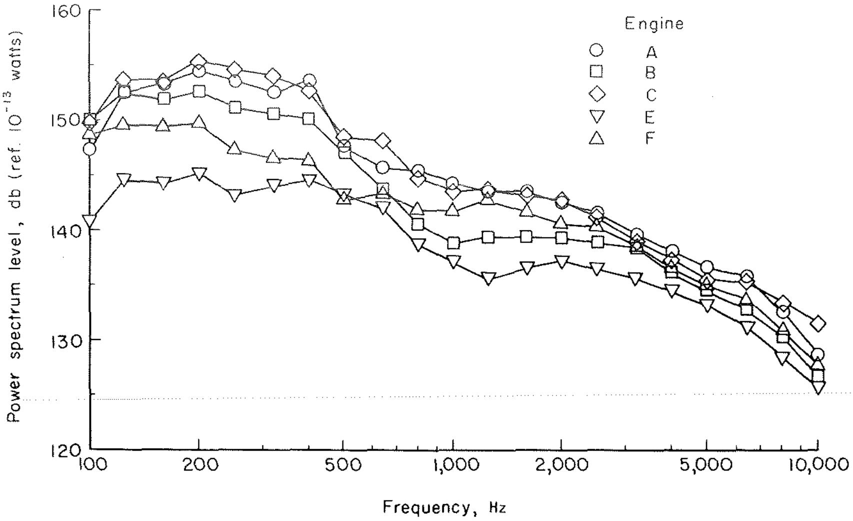


FIGURE 4.—Power-spectrum level in decibels as a function of frequency for five rocket engines.

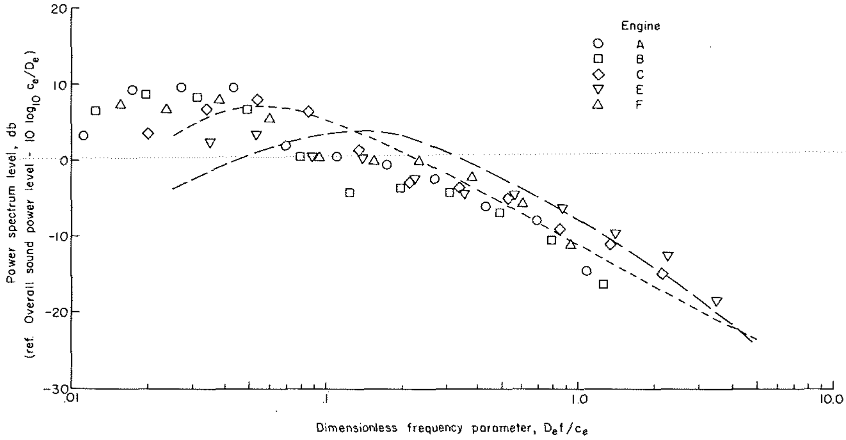


FIGURE 5.—Generalized power spectrum of rocket noise.

the ground noise was measured, the pilot was directed to advance the engine thrust to maximum. As the aircraft accelerated, both the Mach indications of the air-speed indicator and the pilots' statements relative to the indicator readings were recorded, together with the noise levels produced in the microphone. When the aircraft reached its maximum-rated forward speed, the engine was cut back to idling power again to establish the background noise level under the higher speed conditions. The data derived from this procedure indicated that the near-field sound-pressure levels of noise produced by the jet were independent of Mach numbers from 0.35 to 0.70, and within the ±1 dB readability of the data. The only change noted was the observed value of sound-pressure levels, which decreased with increasing pressure altitude.

Because of the difficulty in measuring the noise fields of any jet-noise source in truly free space, it is necessary to obtain dependable measurements made in a real ground plane that will be usable in the free space case. A study by Howes of Lewis Research Center is directed particularly toward determining the free-field spectrum of subsonic-jet noise from measurements made in the presence of a ground plane (ref. 14). In this study, the effect of a reflecting plane on the propagation of jet noise was investigated theoretically and experimentally.

In the past, the effects of a ground plane on acoustic measurements have been of little significance in conventional acoustics. Most sound has been generated by acoustic sources at highly localized positions, and it has been normally measured at single frequencies or in well-defined narrow bands. It has been possible, therefore, to substitute for actual ground-plane effects by providing a sound source representing an image of the real sound reflected in the ground plane. Because jet noise originating from an extended region in the exhaust stream of the jet is extremely variable in wavelength and intensity, it is doubtful that a simple image-construction technique of the effect of a nearby plane would give adequate results. Previous studies of this subject gave theoretical results regarding the decay of noise with distance and the conditions of a truly reflecting ground plane (refs. 15 and 16). Howes, however, attacked the subject experimentally and expanded the theory in the process.

The experimental tests were designed to determine: (1) the significance of ground-reflection effects, (2) whether reflection effects can be disassociated from atmospheric disturbances, and (3) if reflection effects can be evaluated quantitatively. In the theoretical analysis, it was found that the decay of noise as a function of horizontal distance from the source is only slightly dependent upon the shape of the noise spectrum, and the decay of white noise as a function of distance is a practical representation of jet noise. The loci of maximum and minimum fluctuations of decay in space are functions of the receiver bandwidth. The acoustic-path length of reflected noise in excess of that of direct noise produces only a negligible reduction in the average decay rate (inverse-square law).

The experimental tests were concerned mainly with measuring the horizontal noise propagation at azimuths of 30° and 330° from a small air jet located 10 ft above the ground plane. From these measurements, it was found that the effect of ground reflection on jet-noise propagation was significant in the outdoors. The decay rate of the overall sound-pressure level as a function of distance from the source was in accordance with the inverse-square law beyond 20 ft from the source. The onset of the acoustic far field occurred at approximately 10 wavelengths from the source. Fluctuations of the noise decay in space were measurable quantitatively, and they were as large as 10 dB from peak to valley for ⅓ octave-bandwith measurements. These fluctuations were obscured, however, for ⅓-octave bands having mid-frequencies greater than 2000 Hz. Measured jet-noise spectra were correctable to yield corresponding free-field spectra, and the shapes of the corrected spectra were found to be independent of distance from sources in the far field, as predicted by theory. In proceeding from the near field to the far field, the peak frequency of the noise spectrum increased in qualitative agreement with theory.

The specification and prediction of noise created by jet turbulence is inhibited by the failure of theoretical relationships derived by Lighthill and others to give simple numbers with which these formal relationships can be used to produce specific sound-level values. Consequently, the sound level is measured under one set of circumstances, after which the theory is used to predict the reaction of the sound level under a related but different set of circumstances. In effect, the principle of similarity is generally applied by researchers in this field; for example, the prediction of a situation is made based on a related one about which certain internal relationships are known.

Howes of Lewis Research Center has concluded that, when conditions of similarity are satisfied, noise characteristics should be uniquely describable nondimensionally in terms of characteristic flow velocity, a characteristic length, and nondimensional space coordinates (ref. 17). The same principle is discussed in considerable detail by Townsend (ref. 18). In Howes' report, the possibility of applying the principle of similarity to the near field noise of subsonic jets is discussed. In considerable detail, the instrumentation of the experimental program, is described, and graphs of sound-pressure levels are presented, showing the two-dimensional distribution of levels around the jet nozzle for a wide range of operating conditions. The report concludes that the similarity relations proposed by Greatrex (ref. 19) are satisfactory for predicting the characteristics of the fluctuation-pressure field for intermediate values of the flow and geometric variables, if the fluctuation-pressure characteristics are known for two sets of conditions. The validity of the similarity parameters, and hence the predicted pressure characteristics, may be considerably reduced if nozzles having different profiles, or jets having different temperatures, are considered. This is especially true for regions near the nozzle itself.

The report is a good introduction to the mechanics and general analytical procedures that are applicable to near-field noise studies. It should be of considerable value in general industrial applications because the near-field region is of particular interest to the non-aerospace engineer.

Another report by Howes, which is one of a series on the use of the principle of similarity, deals with the problem of measuring far-field noise (ref. 20). Although noise sources of this sort are of less general importance in non-aerospace applications than the near-field sources, the report is valuable for its development of the theoretical background and applicability of the principle of similarity. Extensive far-field jet-noise measurements were related to Lighthill's theory of aerodynamic noise. On the basis of the new as well as previously developed data, all correlations for subsonic jets were generally good. The optimum value of the acoustic-power coefficient was found to be 3×10^{-5}. It was established, however that in the case of supersonic jets, no adequate relation exists for predicting total acoustic power from the geometric and fluid properties over any wide range of flow conditions.

Methods of determining the acoustic efficiency of high-thrusts boosters are discussed in a report by Guest (ref. 21). The noise output of boosters with mechanical-power outputs of between approximately 2×10^{7} W and 10^{10} W are considered in this study. The acoustic efficiency is defined as the power ratio of the acoustical output of the rocket to its mechanical output. The mechanical output is expressed as 0.678 × (thrust in pounds) × (exhaust jet velocity in fps). When the acoustic efficiency, as defined for boosters within the indicated power range, is plotted against the mechanical power, curve *A* of figure 6 is obtained. The curve indicates that the acoustic efficiency falls off as the rockets get larger, which is convenient because acoustical outputs of the largest rockets plotted are approximately 50 MW. Curve *B* of figure 6 (ref. 22) indicates that acoustical efficiencies should be higher than actually measured. It is significant that curve *B* represents rockets with thrusts of less than 150 000 lb. Obviously, some new mechanism must be introduced to justify the shift from one curve to the other.

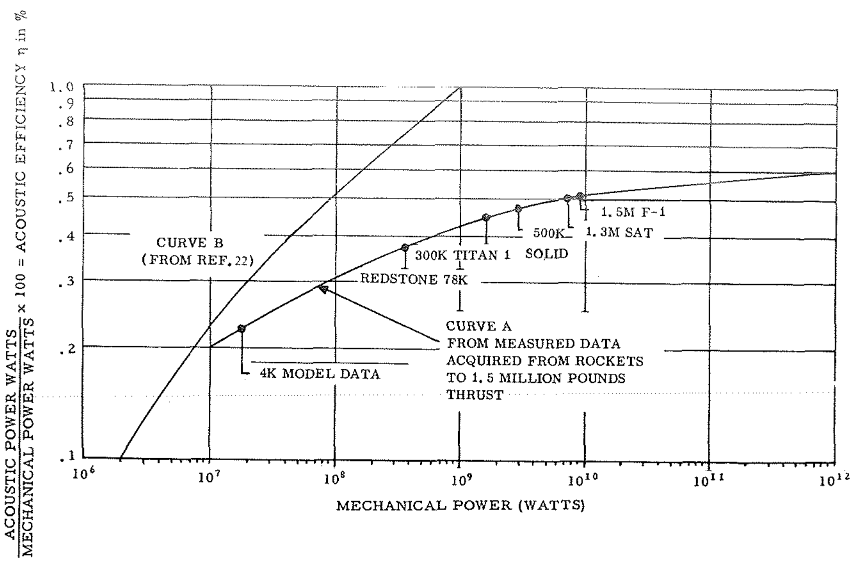


FIGURE 6.—Acoustic efficiency trends.

Most theories of jet-noise generation show that, as the thrust level of a jet is increased, the center frequency of the characteristic noise spectrum shifts to lower and lower frequencies. However, when jets as large as the Saturn V were first tested, it was found that there was more low-frequency noise (below 100 Hz) than predicted. The source of this low-frequency noise is presently under investigation.

Some researchers think that the combustion process within the rocket chamber contributes to the overall noise output. It has been observed that, if the noise of the rocket is calculated only by considering the composition of the exhaust gas and the velocity with which it interacts with a relatively stagnant atmosphere, the low-frequency noise is of less magnitude than that of actual experimental measurements. It is believed, therefore, that the excess low-frequency noise is generated from either the combustion within the chamber or the continuation of combustion as the gas is ejected from the combustion chamber. Thus, if combustion continued out from the chamber into the atmosphere, additional low-frequency noise could be generated.

Possible sources of the additional noise from combustion are discussed in a report by Bollinger, Fishburne and Edse of Ohio State University (ref. 23). A small liquid-fuel rocket was operated over a range of fuel-oxidizer ratios, and measurements were made of the spectrum of the sound sensed by microphones that were spaced along the jet stream. Results obtained from using normal to extremely rich fuel mixtures indicate no observable effect on the spectrum, but when lean mixtures were used, an increase in low-frequency noise was noted. It was also observed that the microphones nearest the jet-exhaust had an increase in low-frequency energy, and that the enhancement of low-frequency energy disappeared completely towards the end of the jet stream. Some tentative conclusions were made as a result of these observations. It was established that the combustion process affects the generation of low-frequency noise. It was considered possible that low-frequency noise was generated entirely within the combustion chamber, and that it was, in fact, the extra noise that could not be sensed above the normal jet-stream noise by the microphones located at points on the downstream portion of the jet. Since no far-field measurements were made, however, the test was not conclusive in its results. The noise within the combustion chamber and that generated in the jet stream itself could not be separated. Although there is some indication that unburned fuel in the exhaust jet reacts with the surrounding air, there was no specific evidence of this, because no chemical instrumentation was applied in the tests.

The Thermal Structures Test Unit at Langley Research Center employs an immense blowdown tunnel with an exit throat of 6 ft by 9 ft. When a full head of compressed air is released from this throat, a thrust of 475,000 lb is created, which is an impressive noise generator. A detailed noise survey of the tunnel operation was made to determine the extent of damage to personnel and structures in the vicinity. A 97-ft-long exhaust diffuser was set up in the tunnel, and the effect on the noise output was estimated. Because the tunnel produced a cold jet, it was possible to make better near-field noise measurements than in hot fuel-burning rocket exhausts of comparable thrust, since the environment in the vicinity of the hot exhaust is much more severe. Near-field noise measurements had been made previously on small hot jets, and this was the first opportunity to test this type of noise on a large scale. The report of the test (ref. 24) includes some graphic presentations which give a perspective of the scale of noise levels found in a fairly simple jet. The wideband sound levels, with and without the diffuser, are illustrated in figure 7. In figure 8, the directional pattern of the noise is shown in terms of actual sound pressure levels at a distance of 450 ft from the tunnel. The report concludes that the large area of intense random noise adjacent to the exhaust jet can be used effectively for acoustic environmental

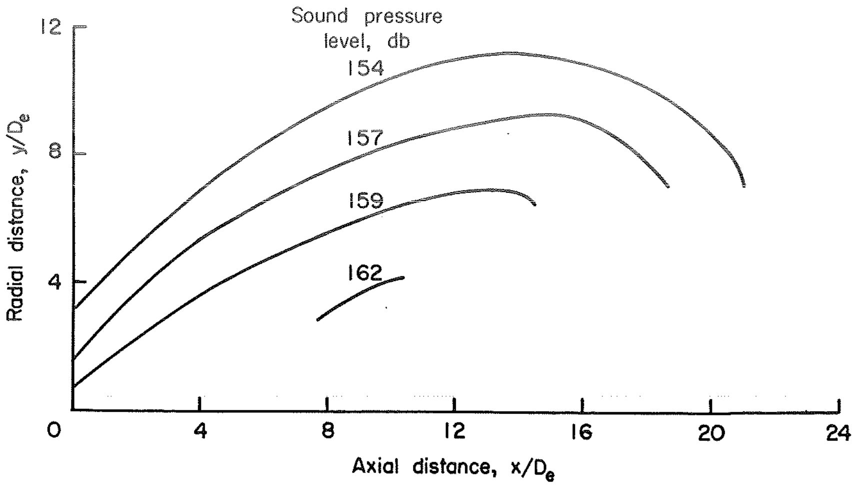


FIGURE 7a.—Wide-band near-field noise contours of exhaust jet of 9- by 6-ft thermal structures tunnel operating at $M_e = 2.68$; frequency range, 20 to 2400 Hz.

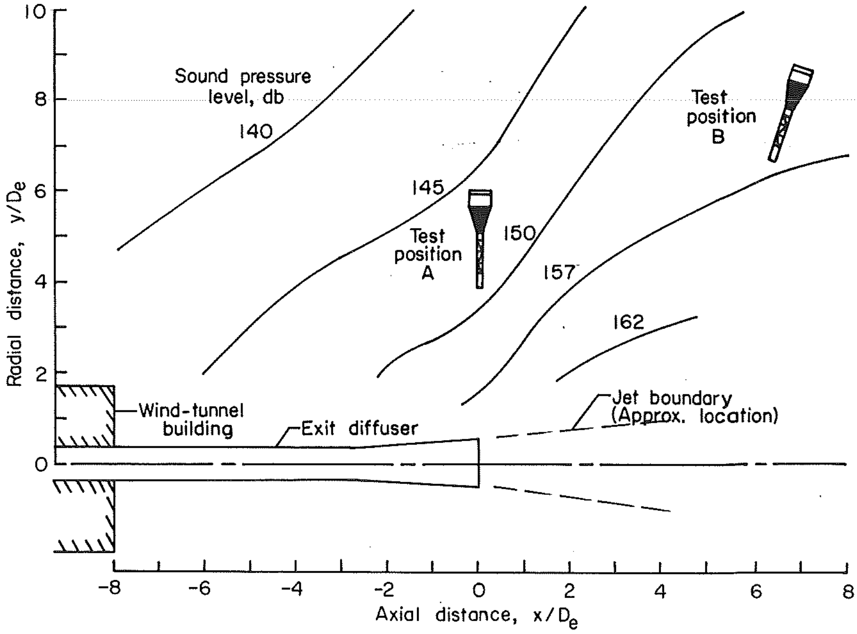


FIGURE 7b.—Wide-band near-field noise contours of exhaust jet of 9- by 6-ft thermal structures tunnel with diffuser installed; frequency range, 20 to 10,000 Hz.

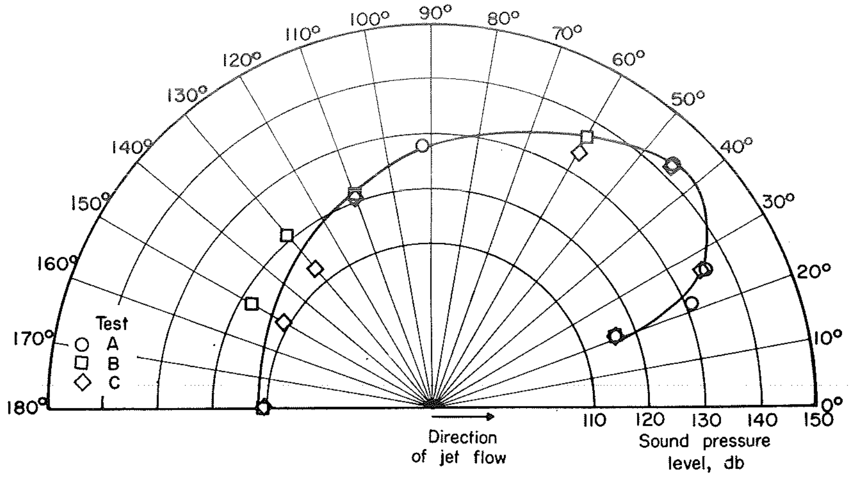


FIGURE 8.—Angular distribution of far-field noise measurements of exhaust jet of 9- by 6-ft thermal structures tunnel operating at $M_e = 2.68$. (Data adjusted to $R = 450$ ft.)

testing of very large components or complete structural units. Indeed, the entire Mercury capsule was tested at a point in the noise field which had approximately the same sound level as that expected at a Mercury test lift-off.

EFFECTS OF UPSTREAM TURBULENCE AND BYPASSING

As turbofan engines with higher-bypass ratios are adapted to aircraft propulsion, the noise from the turbulent exhaust streams will became less important in the overall process of noise generation. Obviously, compressor noise of substantially single-frequency sound will become a most significant noise source. However, the airflow into and around the jet itself will become more complex, so input turbulence may become a major source of noise. In most jet-noise theory, it is assumed that input air flows perfectly smoothly, and its effect on the exhaust is not considered.

Howard and Laurence of Lewis Research Center have studied the effect of input turbulence on the net noise output (ref. 25). They inserted screens ahead of the jet combustion chamber to modify the input flow, and measured the effect on the output.

A hot-wire anemometer was used to measure the fluctuating longitudinal component of the turbulent velocity in the mean flow downstream from the screens, which were inserted in the jet directly at the exit of a converging nozzle. The data were recorded magnetically and were processed by cross correlation as well as by other means. The cross-correlation process provided considerable information about the structure and scale of the turbulence. The scale of the turbulence was expected to have some relationship to the size of the openings in the screens. The study concludes that:

1. The intensity of turbulence in the central core of subsonic jets was increased by the screen at the circular nozzle exit. In general, most of the increase occurred near the nozzle in the high-velocity core. The turbulence intensity proved to be a linear function of the mesh size near the center line of the jet for at least five diameters downstream of the nozzle exit. At the outer edge of the jet flow, however, the turbulence intensity was not a linear function of mesh size.
2. The presence of the screens in the jet caused some turbulent energy to be redistributed from low- to high-frequency bands near the nozzle exit. The large-mesh screens appeared to damp out peaks in the spectrum due to vortex shedding by the exit lip of the nozzle.
3. The turbulent-eddy size (scale) is a linear function of distance from the nozzle exit, and is greater than the size of eddies in comparable jets without screens.
4. In Lighthill's theory, it is postulated that the noise output of a subsonic jet is proportional to the square of the turbulent scale and to the eighth power of the turbulent-velocity fluctuation. It follows from conclusions 1 and 3 that the noise output of a jet in which screens are mounted may be greater than that of a jet without screens. If, however, a decrease in mean velocity occurs simultaneously with the introduction of the screens, the effect may, and usually does, overpower the effects of the increase in scale and in intensity.

Gordon and Maidanik also have considered the complications in jet noise production caused by changes in the input-air stream (ref. 26). Their experiments consisted basically of inserting a flow spoiler into a model air jet a short distance upstream from the exit plane of the jet pipe, and making exhaustive and accurate measurements of the total broadband-sound power radiated by such a system. From an analysis of the data, it was possible to confirm that the spoiler noise was basically a dipole process.

Figure 9 is a schematic presentation of the many interacting mechanisms considered in the analysis. The main spoiler-related sources are the dipole types shown in the pipe, which are generated at the pipe walls or by the splitting action of the spoiler. Based on the assumption of dipole generation at the spoiler,

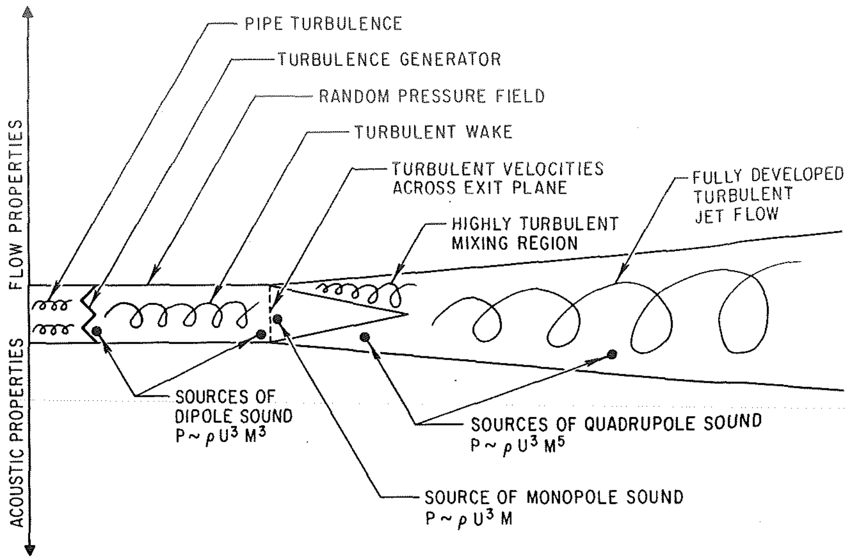


FIGURE 9.—Schematic illustration of the noise produced by jet turbulence.

the following expression is derived for the total sound power radiated:

$$P_A = k\ (P_o - P_a)^3\ D^2/\rho_a^2\ c_a^3$$

where P_A is total sound power radiated, k is a constant with a mean value of 2.5×10^{-4}, $P_o - P_a$ is pressure drop across the spoiler, D is pipe diameter, ρ_a is the density downstream of the spoiler and c_a is sound speed in the same region. The derivation shows that this expression is supported if the radiated power is independent of Reynolds number ($U_l\delta/\gamma$, where U_l is the velocity in the wake of the spoiler, δ is the thickness of the wake of the spoiler and γ is the kinematic viscosity). The radiated power is plotted against Reynolds number and for most cases shows almost complete independence, confirming the assumption. Likewise plots of octave-band power versus Strouhal number ($f\delta/U_l$), the usual frequency-normalizing expression used in these studies, show good tracking of data over a wide range of air velocities for any given spoiler angle of attack.

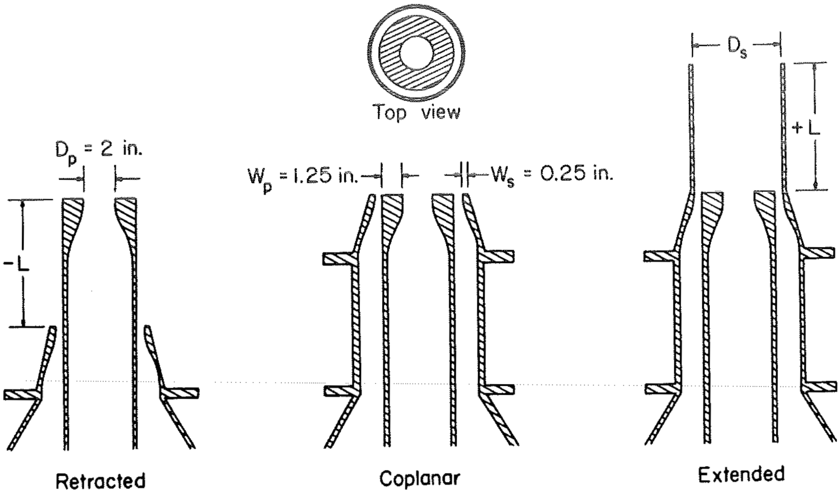
Where the data do not plot in confirmation, there are components that vary as if there were quadrupole sources (power proportional to eighth power of velocity). When a new factor is added to the top of the fraction in the expression for power radiated, the data then track very well. (This factor also appears in the normalized full-spectrum or octave-band power level and is $1-f/f_o$, where f is the center frequency of the range plotted and f_o is a frequency apparently determined by flow dimensions. When f_o was made 4000 Hz, the improvement in tracking occurred.) This is a rather complete exposition of a type of high-speed-flow-related sound generation that may be encountered often in non-aerospace fields.

The mechanism that produces noise in a bypass jet as represented by a turbofan aircraft engine is more complicated than that found in a simple turbulent jet. Bypass-jet noise is created at the output of two concentric jets. The inner jet in the engine has high velocity and a high gas temperature. The outer jet has generally a lower velocity, may have a higher volume of working fluid, and is cooler than the inner jet. Some or all of these conditions occur in industrial processes in which an injecting or aspirating principle of pumping is used. Studies related to this field were undertaken by Kantarges and Cawthorn (ref. 27). Their report includes a description of the Langley Noise Research Facility, which may be of interest to those considering the development of a similar facility for industrial use.

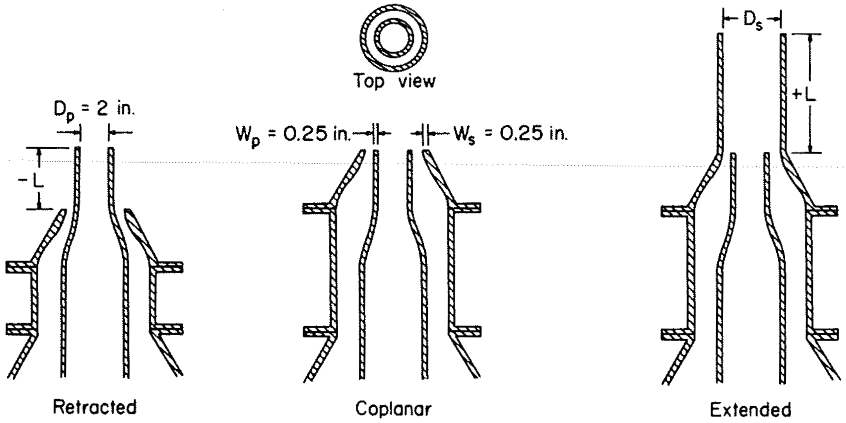
The investigation constituted an evaluation of the noise from concentric bypass jets with which were employed subsonic primary-jet nozzles of two-inch diameter and having two different wall thicknesses, and which operated at a constant exit pressure corresponding to a Mach number of 0.95 in still air. Two secondary nozzles having different diameters were operated at several subsonic-pressure ratios. Retracted, coplanar, and extended positions of the secondary nozzles relative to the primary nozzle were tested. To investigate temperature phenomena, primary-jet stagnation temperatures of 70° and 1500° F were used while the secondary air was left unheated. The nozzles were operated with bypass ratios (ratio of direct- to secondary-jet volume) up to 8.0. The geometry of the retracted, coplanar, and extended forms of secondary nozzles is shown in figure 10.

The results of the study indicated that (1) maximum sound pressure levels were found at the 30° azimuth for most of the cases tested; (2) maximum sound pressure levels tended to shift toward the 45° azimuth for the highest ratios (primary to secondary); (3) sound spectra of the primary jet peaked broadly within a range of from 1000 to 4000 Hz; and (4) the spectra of the bypass jet were similar in shape to those of the primary jet, except for a trend toward lower sound pressure levels at the higher frequencies.

These studies suggest that the addition of unheated secondary



(a) Thick-walled primary nozzle.



(b) Thin-walled primary nozzle.

FIGURE 10.—Jet nozzle configurations.

air to an unheated primary jet usually causes an increase in the noise power, but when unheated secondary air is added to a heated primary jet for bypass ratios up to 8.0, there is no appreciable increase in the turbulent-noise power. In general, the test results for thin-walled primary nozzles showed less variation than those for the thick-walled nozzles; thus, much less sensitivity to the relative location of the secondary exit was indicated.

JET CLUSTERING AND DEFLECTION

In 1961, when it was apparent that clustered tail-mounted jets were becoming important in turbojet aircraft, tests of noise in jets with rectangular slotted nozzles at various spacings were made at Lewis Research Center (ref. 28). It was found that, by adjusting the spacing, a reduction of 50% in total radiated acoustic power could be obtained from a nozzle with a single opening at both subsonic- and supersonic-exhaust speeds.

The ratio of the space between nozzles to the width of the rectangular nozzle for which minimum acoustic radiated power was obtained was 2.0 for subsonic flow, and 1.25 and 1.5 for supersonic flow. It was also noted that, by adjusting the spacing to obtain minimum acoustic-power radiation, a significant reduction in the intensity of the power spectrum in the low- and mid-frequency regions would occur. This experiment, performed with air jets scaled down in size approximately 10:1, correlated well with an equivalent full-size jet experiment. Because the test measured far-field noise at some distance from the nozzles, the results may have little nonaerospace application. However, the reduction in noise occurs as a result of a specific geometric pattern, which may lead to interesting developments of broad applicability.

Smith and Brown conducted a scale-model test program to determine the acoustic field generated by hydrogen-fueled rocket engines of high chamber pressure in various cluster configurations (ref. 29). Because the difference between the center of the noise spectrum of a single engine and that of an equivalent engine composed of eight small clustered engines was too small to be observed reliably, the tests were conducted in two phases. The second phase included testing as many as 12 clustered engines in an effort to obtain more easily observable spectrum shifts.

Various researchers have developed theories describing the effects of clustered engines on both performance and acoustic radiation. In the Smith and Brown study, many of these theories were tested in various degrees of completeness but with rather poor success. The approach that appeared to have the best correlation with the measured data was developed by Potter and Crocker of Wyle Laboratories (ref. 30), who found that the acoustic efficiency for the entire series of engines, from 1 to 12 sub-engine groups, was approximately the same, with a few cluster sets showing lower efficiency than the others. The measured efficiencies correlated poorly with data from other investigations.

The overall directivity of the noise source was found to vary with the number of nozzles, the peak output shifting from 70° to 50° from the stream direction for the single engine and the 12-nozzle cluster, respectively. These data compare fairly well with those of other reports. Apparent source locations and curves of third-octave-band directivity varied widely, as expected. Near-field data correlated poorly with calculations made by using the effective diameter as the correlating dimension. The effect of ground-plane absorption that was observed throughout the tests was greater than that indicated in the work of other investigators (see ref. 14).

Another external influence that affects jet-noise output is the deflecting of the jet. In seeking new ways of improving the take-off and landing characteristics of aircraft, and in developing vertical- and short-take-off-and-landing aircraft, researchers have analyzed in considerable detail the behavior of a deflected jet. Jet deflection is usually accomplished by using the equivalent of a landing flap to change the direction of the exhaust from a conventional aircraft turbojet engine. In this manner, the jet is directed downward at an angle that causes a vertical component of thrust to be produced. It is important, in the case of aircraft, to determine if the jet noise contributes significantly to the fatigue of the surface deflecting the jet. In nonaerospace applications, the jet may not be as hot as in turbojet engines so that the effect of heat contributing to failure may be absent. However, the acoustic-noise level must be considered as a potential source of trouble in any application. Tests of models one-eighth the size of commercial turbojet aircraft under full-scale simulated conditions were undertaken by Fink of Langley Research Center. The report of these tests (ref. 31) indicates that acoustic-fatigue failure might occur in the deflecting panel. The experiment extended the work of previous investigators with cold jets and confirmed other test results obtained from jets produced artificially rather than by working turbojet engines.

ROCKET NOISE LEVEL PREDICTION

A general review of methods used to predict the acoustic output of rocket engines is contained in a report by Potter and Crocker of Wyle Laboratories (ref. 30). The extreme intractability of accurate sound prediction is stressed in this report. The investigators noted that perhaps the best estimate of the total acoustic output of most rockets is 0.5% of the mechanical power; however, they suggest a more complex formula. In addition, they observed that near-field spectra, measured along the 10° line from the exhaust direction, can be predicted fairly accurately. The effects of clustering and deflection are also predictable after elaborate calculations of the exhaust-flow conditions are made.

NOISE FROM COMBUSTION INSTABILITY

Flame-driven resonant oscillations in burner tubes (singing flames) have been observed since the eighteenth century. A severe form of the phenomenon is the screech that occurs in high-performance rockets and boosters. In high-performance rockets, a very intense sound is created by a resonant instability occurring in the burning process. The intensity of this sound may destroy the effectiveness of the rocket and even the rocket structure itself. The correction of combustion instability, particularly that of hydrogen-oxygen rockets, is of considerable interest to NASA, but of less interest to the nonaerospace industry. However, the principles involved in oscillation suppression are applicable in many areas; for example, the reduction of the resonant roar in the home oil burner.

Several studies on screech suppression have dealt with nonacoustic methods of reducing noise-producing combustion instability, while others have been concerned with the application of purely acoustic methods of suppression. Wanhainen, Hannum and Russell of Lewis Research Center have investigated concepts of improving chemical-physical stability in hydrogen-oxygen combustion (ref. 32). One method of improving stability that they examined was that of controlling the radial distribution of the propellant injection. By concentrating the injection into the center of the combustor, a very detrimental effect on the longitudinal-mode stability was observed. Under unstable conditions of distribution, increasing the engine-contraction ratio, by reducing the nozzle-throat area into which the burned and burning gases travelled, lowered the hydrogen temperature at which the screech was encountered and thus improved stability. The extent to which hydrogen-injection temperature must be reduced before instability begins is universally used as a criterion of stability in this type of rocket.

A purely chemical technique of adding fluorine to the liquid oxygen, up to 30% by weight, produced no significant effect on the stability characteristics of most injectors tested, but it slightly improved the engine performance. Extending the oxidizer feed tubes away from the injector face stabilized the combustion of some injectors to the lowest temperature obtainable, but the improvement in stability was accompanied by a loss in performance. Providing porous injector faceplates improved the hydrogen-temperature operating limits of a particular multi-element injector by 25° over the range of oxygen-fuel ratios investigated. Changes in the radial distribution of nozzle areas were also tested. Wagon-wheel-type nozzles improved hydrogen temperature trends, reducing unstable operating-temperature limits by as much as 20°.

The last stabilizing measure attempted involved the cooling of the chamber walls by diverting up to 20% of the fuel along the walls. This technique produced no major changes in stability, and performance decreased 2% to 3% for each 10% of the total hydrogen diverted for film cooling.

Further research to find purely mechanical non-acoustic methods for improving the stabilization of combustion in a rocket-type combustor was undertaken by Hannum and Scott of Lewis Research Center (ref. 33). This work involved a cursory examination of the probability that, by using baffles at the face of the hydrogen injector, stability could be achieved. Devices were considered that could be used (1) to compartmentalize the combustion chamber; (2) to perform simple acoustic damping; (3) to obstruct the acoustic paths in the combustor; and (4) to reduce the cross-velocity effect of the local mixture ratio. The criterion of stability was determined to be the hydrogen-injection temperature at which the combustion is stable in typical hydrogen-oxygen-fueled rockets. The baffles were thick-walled fins of various forms. Many were wagon-wheel shaped in purely radial or modified-radial forms with three to seven spokes and open centers. Three different egg-crate types of baffle having 7, 25 and 100 compartments, respectively, were also used.

The results of the experiment indicated that injector-face baffles 2 in. long used with maximum compartment dimensions as large as 9.1 in. produced acoustic stability at the minimum hydrogen-injection temperature of the testing facility, 55° R. Regardless of the number of spokes or compartments used, the system was stable with 2-in. baffle sections. With injector-face baffles 1 in. long, stability could be achieved down to a temperature of 55° R when the average maximum compartment dimension was less than 4 in. This technique for reducing screech is applicable to rocket combustors in which mixtures other than hydrogen and oxygen are used.

NASA research on the subject of screech suppression is of general interest because it deals with the prevention of instability in combustion. However, the investigations have been limited to rockets in which exotic fuels are used, and, consequently, have little applicability to industrial processes. Nevertheless, the principles involved and the general approach used by the researchers may perhaps be valuable for consideration in other fields of investigation.

Investigations of other ways to reduce combustion instability involved determining how the dimensions and shape of a combustion chamber, together with the size of its input and output openings, affected stability by enhancing acoustic absorption in the chamber itself. In 1966, a group of U. S. Navy researchers undertook a study of the most prevalent form of unstable combustion in rocket motors, which involved gas oscillations having the frequencies and other physical characteristics associated with one or several of the acoustic modes of the motor cavity. The report of this research is an excellent source of reference material and is valuable for its discussion of acoustic-measuring techniques (ref. 34).

The study dealt primarily with the geometrically simple problem of determining the relation between the acoustic losses in axial modes and the *J* value of the cavity (the ratio of the nozzle-throat area to the propellant-grain-port area). An examination was made of the effect of this ratio on the overall acoustic response of the chamber when excited by sinusoidally varying gas flow into the chamber under cold conditions. A specially designed rotary valve was used to oscillate a portion of the incoming air flow. Driven by a 5-hp variable-speed motor, it produced an approximate sinusoidal modulation of from 180 to 1300 Hz.

For the axially symmetric geometries studied, it was found that:

1. Nozzle-radiation losses increased approximately linearly with *J*.
2. Nozzle losses were independent of the manner in which *J* is changed, either by a change in the grain-port area or the nozzle-throat area.
3. The nozzle losses determined by the experiment were greater than had previously been predicted. However, the results agreed substantially with a theory in which a linear, no-flow nozzle admittance term and the Hart-McClure convective term are applied (ref. 35). For engineering design purposes, the nozzle-attenuation constant, including both the radiation and convection of acoustic energy for the first longitudinal-mode oscillation, could

be expressed as $a=1.59\frac{cJ}{L}$ where a is the temporal-damping constant ($\sec^{-1}$), c is the velocity of sound, J is the ratio of nozzle-throat area to grain port area, and L is the length of the motor chamber.

4. The data and the theoretical analysis showed that, under the test conditions, both the acoustic bulk and wall losses were negligible compared to the nozzle-radiation losses for the axial mode of oscillation.

5. The experimental method was found to be a suitable and promising technique. The steady-state-resonance method was applicable through the J range of practical interest, and for attenuation studies, either with or without critical nozzle flow.

In addition to the steady-state resonance method of determining the attenuation constants, the possibilities and limitations involved in using two decay-measurement techniques were investigated. The pulse decay technique was not satisfactory because the method involved the introduction of hot combustion gases and solid-phase matter into the chamber, and also because it resulted in multiple-mode excitation. The steady-state-decay technique was found to be limited to rocket chambers with decay constants less than 150 $\sec^{-1}$, corresponding to geometries with small ratios of nozzle area to grain-port area (J less than 0.14). The results of these tests were valid, however, for independently confirming the attenuation constant in the range where it could be applied.

The potential effects of combustion-chamber acoustical absorption on rocket-combustion stability is described by Wieber of Lewis Research Center (ref. 36). One of the decay techniques of measurement that was found unsatisfactory in the previously discussed report (ref. 34) was used in this study. The problems noted previously may have occurred because gas flowed through the chamber in those tests. In Wieber's experiment, however, no flow was permitted. Cold acoustic-bench tests were made to obtain decay coefficients of cylindrical acoustical modes in simulated rocket-combustion chambers with no through-flow.

A group of researchers at Lewis Research Center investigated the effects of using specific acoustic-damping devices to suppress combustion instability (ref. 37). The test rocket of 20 000-lb thrust was operated at a chamber pressure of 300 psia over a range of oxidizer-fuel ratios from four to six. The liners consisted of simple relatively thick metal rings of copper or steel, in which resonators were created by drilled holes. Each liner had holes of the same size. Liners $\frac{3}{16}$-, $\frac{3}{8}$-, and $\frac{3}{4}$-in. thick with holes ⅛-, ¼-, and ½-in. in diameter were tested. The liners were separated from the inner surface of the outer wall of the combustion chamber distances of from 0.41 to 0.975 in. The investigation yielded these results:

1. High-frequency combustion instability in hydrogen-oxygen rockets of the size tested can be suppressed with a properly designed array of Helmholtz resonators.
2. The liner-cavity-gas temperature, which varied with such liner variables as aperture size, open-area ratio, and axial position, has a strong effect on liner-absorption characteristics. A variation of cavity-gas temperature with injector-element size and spacing, contraction ratio, and the propellant combination could be expected; thus, unless a means of predicting or controlling cavity temperature is available, no rational design procedure is possible.
3. Analytical predictions based on acoustic theory were in limited agreement with experimental results, provided the effect of flow past the apertures was considered in the calculation of the absorption coefficient. A side velocity of 280 fps caused the best agreement between analytical and experimental results for a liner $\frac{3}{16}$-in. thick. Additional data evaluating the effect of flow past the apertures are required before liner absorption characteristics can be predicted.
4. Calculated absorption coefficients of 0.25 or higher, evaluated for absorption at the cavity-gas temperature typical of stable combustion, and at a sound-pressure level of ±13 psi, were required for the injector used in these tests to eliminate screech at a hydrogen-injection temperature of 60° R (minimum available).
5. It was not necessary to use full length liners in the combustor to suppress acoustic-mode instability. A liner 17% as long as the combustor, which was positioned at the injector end of the thrust chamber, provided stable combustion to a hydrogen-injection temperature of 58° R.

The technique of suppressing combustion oscillation with mechanical damping devices was considered in a study for Marshall Space Flight Center in 1967 (ref. 38). In this study an extensive evaluation was made of the acoustic properties of potential combustion-chamber liners. An important point was made that, because conventional acoustic-impedance is usually measured in the absence of flow, some anomalies in the data obtained are probably attributable to the difference between flow and no-flow conditions. Efforts were made to determine the effects on liner absorption of simultaneous flows of gas through and past the apertures, to investigate the bandwidth characteristics of absorbing liners, and to observe the effects on absorption of differences in gas properties between the liner apertures and the combustion chamber. Measuring acoustic impedance at the extremely high levels of sound encountered under conditions of unstable combustion was of particular interest, since a nonlinear resistance is assumed to be included in impedance under the circumstances. By using a standard impedance-measuring device, the investigators were able to measure the resistance of resonator arrays of the Helmholtz type at incident sound-pressure levels of from 121 to 171 dB. An electropneumatic high-intensity sound generator was used for these tests. An impedance tube modified with flow ducts was used to determine the effects of simultaneous flow and the acoustic resistance of liner samples. Tests were also conducted with flow past the apertures. In the simultaneous-flow experiment, the velocity past the apertures was varied from 25 to 490 fps, and the flow-through velocity, from 100 to 400 fps. The results of the experiment indicated that flow-past or flow-through causes the acoustic resistance to increase in proportion to the flow velocity. Flow-through was observed to increase resistance by seven times over that caused by flow-past of the same velocity. With simultaneous flows, it was found that the effects of flow-past were negligible, because the resistance increased as if only flow-through were present.

In an effort to improve the absorption characteristics of acoustic liners, six different design concepts were evaluated. Increasing the aperture resistance by coupling the liners to the chamber with porous screens was quite effective. Combining high-open-area resonators with low-density-porous backing plates, which increased bandwidths and reduced the amplitude of absorption, proved to be the most effective.

Because large temperature gradients exist between the gas in the combustion chamber and the gases in the apertures and cavities of the absorbing liners, experiments were conducted to determine how the resulting variation in gas properties affected the liner's absorbing characteristics. Because the standard ASTM impedance tube was found unsuitable due to distortion in the standing wave pattern, a special impedance apparatus was fabricated to eliminate the need for standing waves. With this new device, it was found that the effects on sound intensity of a change in the medium through which the sound wave travels can be predicted from one-dimensional theory. Also, if gas properties in apertures and in cavities of an absorbing liner operating in such an environment are known, the acoustic performance of the array can be predicted within the limits of the present theory.

Additional tests of impedance were conducted with a resonator array of 5.4%-open-area ratio using both the standing-wave impedance tube and the pressure-phase apparatus. Comparisons of the data with theory indicated that present theory is inadequate for resonant frequencies ranging above 2000 Hz. Consequently, it was concluded that, until additional research is accomplished to extend the theory of absorbing-liner design in the high frequencies, designs of absorbers for frequencies higher than 2000 Hz should be tuned for operation below resonance.

BOUNDARY LAYER NOISE

A solid object moving at high speed through a gas is resisted by viscosity. This resistance is generated in a thin region near the surface of the body, the boundary layer, in which large mean-velocity gradients normal to the surface exist. Normally, the Reynolds number is large enough so that the motion within the boundary layer is turbulent; that is, unsteady or fluctuating velocities of a random nature are superimposed on the mean velocity of the moving body. These fluctuating velocities produce pressure fluctuations that are evident as sound associated with the turbulence, and as a fluctuating force acting on the surface of the body. In studying the stresses on a body subjected to such forces, interest is directed to their magnitude, since they can excite structural vibration contributing to fatigue failure, and can generate noise both within and without the body. The importance of these forces to designers of high-speed aircraft and rocket vehicles is obvious. In nonaerospace applications, the primary concern is not so much with a body moving through a gas as with a gas moving past the body, such as might occur in a high-speed gas flow in an industrial process. Noise generated in boundary-layer flow is, therefore, of widespread interest in many areas, because such noise is a function of turbulent forces at work.

Many of the early investigations of fundamental aerodynamic noise were conducted by the British. The mechanism of noise generation by turbulent flows over rigid surfaces was studied theoretically by Curle (ref. 39) and Phillips (refs. 40 and 41). Theories on noise excited by turbulent boundary layers and radiated by flexible flat plates were developed by NACA personnel, Corcos and Liepmann (ref. 42), Ribner of the University of Toronto (ref. 43), and Kraichnan (ref. 44). Dyer, Tack and Lambert (refs. 45 and 46) have considered the response of plates and bars subjected to boundary-layer pressure fluctuations, based on the approach suggested by Lyon (ref. 47). Empirical data on the characteristics of pressure-fluctuation fields are needed to confirm these theories. Various measurements of low-pressure fluctuation characteristics have been made in the laboratory on smooth and rigid surfaces. Both subsonic and supersonic measurements have been made of flat plates with smooth surfaces, and rotating cylinders with both smooth and rough (sandpaper-type) surfaces; and they indicate rather wide variations, particularly between the subsonic and supersonic.

It has been extremely difficult, if not impossible, to relate in-flight measurements directly to those obtained in the laboratory. A detailed experimental program is needed, therefore, to determine the effects of speeds up to and including the supersonic range, and to examine, under laboratory conditions, some of the non-uniform effects produced by surface roughness and shock wave impingement on practical vehicle configurations. These practical considerations are also important outside the aerospace field wherever high-speed gas flows are encountered. Several early laboratory studies of boundary-layer pressure fluctuations and some more complex aspects of boundary-layer effects caused by intervention of physical protuberances and shock waves are discussed in this section. The simulation of boundary-layer noise for testing is considered elsewhere in this survey where the subject of acoustically-caused fatigue failure is discussed.

In 1959, Willmarth of the California Institute of Technology performed an experiment in which he measured the properties of the fluctuating wall pressure produced by a subsonic turbulent boundary layer (ref. 48). His purpose was to obtain information about the boundary-layer-induced noise inside an airplane fuselage. The experiment was conducted in a small sound-isolated low-noise wind tunnel made of a brass tube with a 4-in. inside diameter. Pressure transducers of barium titanate were attached to the wall of the tube, and air was supplied through a special silencing duct to the wind tunnel. A sonic throat at the exit of the tunnel prevented the propagation of sound waves from the exit side of the tunnel, keeping the internal tunnel conditions comparatively quiet. A small amount of air was injected at right angles to the main flow just inside the throat of the tunnel through ½ mm-diameter holes. This operation, referred to as "tripping," ensured that there would be a turbulent layer past the transducer.

The report of the experiment describes the techniques of correlating and analyzing the data. A modified digital-computing technique was employed in the analysis. Some interesting conclusions were drawn from investigating the space-time correlations and the spectra of wall pressures in a turbulent boundary layer:

1. The rms wall-pressure fluctuations approach the value $\sqrt{p^2}=0.06q_\infty$ as $d/\delta \rightarrow 0$, (where p^2 is mean-square static pressure, q_∞ is the free-stream pressure, d is the diameter of the pressure transducer, and δ is the boundary-layer thickness) and are independent of Reynolds and Mach numbers at subsonic speeds.
2. The spectra of the wall pressure can be expressed in a dimensionless form. The dimensionless spectra apparently approach a universal function of $w\ \delta^*/U_\infty$ (where w is the angular frequency, δ^* is the boundary-layer displacement thickness, and U_∞ is the free-stream velocity) as the transducer size is reduced.
3. Space-time correlation measurements of the pressure fluctuation whose scale is greater than or equal to $0.3\ \delta$ show that a given pressure pattern is convected at a speed of $0.82U_\infty$ and is essentially destroyed in a distance of 10 boundary-layer thicknesses.

A continuance of the work performed by the California Institute of Technology on boundary-layer turbulence was reported by Weyers in June 1960 (ref. 49). In this report, the experimental procedures that were used, and the measurements and theoretical calculations that were obtained, from investigating phenomena of wall pressure and near-field sound pressure produced by turbulent air flow were described. Air free of turbulence was supplied to the measurement system by passing it through a tube of relatively large diameter that was lined with fiber glass, inside of which were two conventional air-flow sound mufflers. After passing this tube, the air was throttled down to a 1-in.-diameter heavy brass pipe approximately 7 ft long, through which it was passed at a fully turbulent flow of the velocities established for the test. The tests were made in a 1-ft section of the brass pipe, which was replaced by a thin-walled Mylar tubing with a wall thickness of 0.0005 in. A pressure transducer placed against the Mylar wall was employed to measure the actual pressures against the wall that were produced by the turbulence on the inside of the tube. A microphone placed near the wall was utilized to measure the near-field sound output from the turbulent disturbance of the wall. The test portion of the cylinder, despite its thinness, was subject to a variety of mechanical and acoustical resonances; consequently, power-spectra measurements, particularly those of the near-field sound, which were influenced by motion of the entire thin-walled section, indicated that many peaks and valleys were induced by the resonances. The pressure measurement obtained with the barium-titanate pressure transducer placed directly against the wall indicated that the local pressure was little affected by the resonance of the tube, except by that in the immediate vicinity of the transducer.

The ingenious instrumentation developed for this experiment was emphasized in the report, since the mode of vibration established in the test tubing tended to mask some of the phenomena under observation. The experiment revealed that the intensity of the external pressure fields (near-field sounds) varied with the fifth power of the velocity at the center of the pipe. The wall pressure of the pipe, measured with a transducer at the actual surface of the pipe, varied with the fourth power of the velocity at the center of the pipe. It was also observed that the ratio of the rms pressure at the wall to the free-stream dynamic pressure was a constant (0.0078). Similarity laws for the spectra of the wall-pressure fluctuations were also confirmed.

With this rather ingenious experiment, the investigator was successful in confirming turbulent flow and velocity. He also established that, with conventional theory, it was possible to predict accurately the modes of vibration of a thin-walled cylinder under internal pressure when the cylinder was excited by turbulent flow.

The anomalies observed in practical turbulent boundary-layer noise measured under conditions of flight were examined in the laboratory by other researchers. The report of this work contains descriptions of experimental methods used to measure the complex boundary-layer noise phenomena that occur under simulated conditions of aerospace flight (ref. 50). The measurements were made on the sidewall of a trisonic one-foot tunnel. The tunnel is a blow-down-to-atmosphere facility that operates over the Mach number range of 0.2 to 3.5. The operating Mach number in the tunnel is generated at supersonic speeds by fixed nozzle blocks. Speeds in the subsonic and transonic range are achieved by changing the area of a second throat downstream from the test section.

Features of the tunnel that facilitate researching boundary-layer pressure fluctuations include an acoustic muffler in the stilling chamber ahead of the tunnel input, which reduces background noise, and a choked second throat, which prevents sound propagation upstream from the diffuser, even when subsonic speeds are generated in the test section. Thus high teststream dynamic pressure with low background noise can be achieved. The facility was specially modified for this study to eliminate the background noise normally associated with the choked flow over the control valve. This was accomplished by connecting the 8000-cu-ft reservoir of the tunnel with an adjacent 26 000 cu-ft reservoir; thus, when operations were conducted with stagnation pressure equal to reservoir pressure, the choked-valve noise was completely eliminated.

Measurements were made on a 14½-in. circular insert in the sidewall of the test section. Details of the instrumentation, which included differential pressure transducers for measuring boundary-layer pressures as well as pressure distribution through the body of the steam, are described in the report. Boundary-layer pressure fluctuations were detected by a series of flush-mounted condenser microphones installed in a second insert in the sidewall of the wind tunnel. The acoustic data were magnetically recorded in the first series of tests in the FM mode to provide data over the frequency range from 0.01 to 10.0 Hz; and in the second series of tests, in the direct mode, to provide data over the range from 0.1 to 100.0 Hz. A typical wind-tunnel run lasted for approximately 15.0 sec., including tunnel starting and shut-down time. The analyses of the acoustic-frequency data were accomplished by rerecording the data on a multi-channel continuous loop having a running time of approximately 10.0 sec. The data on a loop thus represented that portion of the wind-tunnel run during which essentially steady-state conditions prevailed.

In addition to the two sidewall inserts used for static and fluctuating pressure measurements, two-dimensional shock-wave and pressure-gradient generators were added. The shock generator, which spanned the height of the tunnel, was rotated about one of two pivot points to change the shock angle between 0° and 10°. Expansion angles of from 0° to 5° were also possible with the same arrangement when the forward pivot point was used. The adverse pressure-gradient generator did not operate as originally designed, but, after modification, it produced a change in Mach number of 0.8 in 4 in. A number of roughness elements were also introduced, so that the effects of local perturbations on tunnel sidewall-boundary-layer pressure fluctuation levels could be studied. Four thicknesses of two-dimensional roughness between 0.012 and 0.125 in. were provided, and a second 0.125-in. strip was wound around the leading edge for comparison with the square leading edge. All were one inch in width. A simulated half-scale window 0.050-in. thick was also provided.

The tests are described comprehensively in the report, which may serve as a good guide for researchers undertaking similar investigations in other fields. The conclusions of the study are substantially as follows:

1. The blow-down wind tunnel modified to enable an operation with stagnation pressure equal to reservoir pressure was a satisfactory facility (low-background-noise level) for measuring boundary-layer noise over the Mach range of 0.4 to 3.5 in a single experiment.
2. Measurements of the zero-pressure-gradient boundary layer are in agreement with other results at subsonic speeds, and indicate a pressure spectrum that is flat to values of non-dimensional frequency $f\,\delta^*/U_\infty=.45$ and a truncated fluctuation level of $\sqrt{\Delta p^2}\,T/\tau_0=2.8$ for $f\leqq 44$ kHz.
3. Zero-pressure-gradient results at supersonic speeds show pressure spectra which are flat to $f_0/U_\infty=.15$ and truncated fluctuation levels of $\sqrt{\Delta p^2}/\tau_0=1.2$ to 1.7 for $f\leqq 88$ kHz, a frequency range to which practical vehicle structures can respond.
4. Measurements to determine the influence of favorable and adverse pressure gradients on wall-pressure-fluctuation levels at Mach 3.46 were inconclusive.
5. At Mach 3.46, the impingement of shock waves on the turbulent boundary layer can increase the pressure-fluctuation level by a factor of 20 above the undisturbed case.
6. At Mach 3.46, two-dimensional square-edge roughness elements increase pressure fluctuations by a factor of 5 or 6 above the undisturbed boundary-layer level.

Studies of noise and vibration dealing with the use of models and other scaling methods for examining phenomena that cannot be handled at full scale without difficulty may have important uses in nonaerospace applications. One of these is an investigation by Nacht and Turk, which was undertaken to find the causes of some extreme vibration that had occurred on Atlas launches over the Mach range of 2.0 to 2.5 (ref. 51). Analysis of the flights had shown that specific power-spectral-density peaks occurred at 600 and 900 Hz with a 50-Hz-bandwidth resolution. A wind-tunnel test program was conducted to ascertain if this disturbance had an aerodynamic origin, and to determine specifically whether the boundary layer had an effect on the frequency and amplitude of the pressure fluctuations that were observed.

A $1/10$ scale model of an Atlas-Agena-Mariner C was tested in the Lewis Research Center's supersonic wind tunnel with Mach number, dynamic pressure, and altitude as the primary test variables. Both the original model and a configuration with a redesigned pod were investigated. Dynamic pressure transducers were used to measure pressure fluctuations in the pod area. From the transducer data, rms differential-pressure-coefficient values and power-spectral-density variations were obtained for the areas of greatest activity. In addition, the effect of the boundary layer on pressure fluctuation was examined. Power spectral-density analyses failed to reveal distinct power-spectral levels at model frequencies corresponding to full-scale frequencies where significant power concentrations had been observed. This indicates the possibility that large flight vibratory levels may be caused by pressure fluctuations that excite vehicular structures at their natural resonant frequencies. Studies of the rms fluctuating pressure revealed that flow separation and shock-boundary-layer interaction may contribute significantly to the general level of pressure fluctuations on launch vehicles.

The significance of this research to the nonaerospace field is that, even in a vehicle as aerodynamically uncomplicated as a streamlined launch vehicle, no simple relationships exist and complex interactions between internal structures and external forces are to be expected. Modes of transmission of vibration into structures are discussed later in this survey.

SONIC BOOM

NASA studies concerning the origin and characteristics of the sonic boom may be useful in examining the effects of such shock waves on industrial processes. Efforts have been made to simulate sonic booms in the laboratory, and, in this process, test facilities and techniques have been developed that may prove to be useful in a variety of nonaerospace applications. The following discussions deal primarily with these aspects of sonic-boom research.

In 1963, a NASA conference was held on the general feasibility of supersonic transport. Three papers dealing directly with noise generated by supersonic aircraft were presented at this conference. One was a discussion of factors affecting public acceptance of the sonic boom (ref. 52), a subject which is discussed in detail in Chapter 4 of this survey. Another presentation was a discussion of the effects on aircraft of noise generated by the engines and the boundary layers caused by the supersonic flow past the aircraft (ref. 53). The third paper (ref. 54) provided a good introduction to the complexity of sonic-boom phenomena. It reflected the state of the art (as of 1963) of aircraft shape and its effect on sonic boom. Much of the research on this subject was accomplished during the period of from 1950 to 1958 (refs. 55 and 56).

The phenomenon of sonic boom emanates from a disturbance of the normal atmosphere caused by the passage of a physically large object through it. The cross-sectional area of the object and the distribution of this area along the length of the object are factors which determine the intensity of the sonic boom. These factors are clearly significant in all cases in which supersonic gas moves past objects of any size or shape, and, for some years, have been widely used in aerodynamic studies. Researchers in this field generally postulate that a perfect aircraft should have a constant cross-sectional area over its entire length. Although this concept is not always practical in application, it has been the basis for the design of many high-speed aircraft having a constriction in the fuselage at the point where the wing is attached. In effect, the cross-sectional area of the wing plus the main body remains the same as the cross-sectional area of the body forward of the wing attachment. Although this concept is not applicable to current commercial subsonic transports, it is very important for supersonic configurations.

An approach to calculating far-field shock waves was presented by Whitham in 1952 (ref. 55). Somewhat later, Walkden investigated shock patterns far from the flight path (ref. 56). In 1960, Lansing of Langley Research Center published a report in which he reviewed the theory developed by Whitham for the supersonic flow about bodies in uniform flight, and reduced an integral, which expresses the effect of body shape upon the flow parameters in the far field, to a form that can be evaluated readily for arbitrary body shapes (ref. 57). The basic significance of his report is reflected in the conclusion, which is quoted in part:

> The physical implications of the basic hypothesis for Whitham's modification of linear theory (Communications on Pure and Applied Mathematics, August 1952) have been considered and a brief derivation given of the far-field equations for the bow shock. An integral which determines the effect of body shape upon the bow-shock overpressures in the far field has been reduced to a form which involves only the cross-sectional area distribution and can be readily evaluated for body shapes for which no analytical expression is available. The integral has been evaluated for a number of families of body shapes chosen to investigate the effects of nose angle, fineness ratio, and location of maximum cross section on the bow-shock overpressures. The results of these calculations indicate the following conclusion: In regard to body geometry, the pressure discontinuity in the far field is, to a first order, independent of body shape and depends only on the fineness ratio. (Ed. note: A measure of slenderness of the body shape.) Local details have second-order effects which, in general, can be accounted for only by direct computation of the body-shape constant.

Although the basic area rule involves testing the cross section by taking cuttings of the aircraft at right angles to its longitudinal axis, other sets of cuttings may be taken at various angles to this axis. Cuttings may be taken at many angles to evaluate the effects of shape on drag, lift, and other phenomena. One very significant cutting is directly related to the sonic-boom phenomenon. It is taken at the so-called Mach-angle which has a sine equal to 1/M, where M is the Mach number or the ratio of speed to the velocity of sound. These cross-sectional areas differ quite sharply from those taken in the conventional manner, and are directly related to the value of the lift produced in a supersonic aircraft. It has been established that the lift-determining factors revealed by these cuttings sharply affect shockwave generation.

The report includes a discussion on how these theoretical methods are applied in estimating the far-field overpressure of the sonic boom. In the near vicinity of the aircraft, the overpressure (the amount by which the shockwave sound pressure exceeds the average atmospheric pressure) has a very complex shape because it is made up of many small overpressures produced by all parts of the aircraft—the front and the back of the engine, the front and back of the wing, the nose, and the extremities of each of the various control surfaces. Because these are so complex, no serious consideration is usually given in sonic studies to any factors except the far-field sound pressure, which combines these complex overpressures into a simple sound-pressure pattern. It is this pattern that affects people and structures on the ground.

The far-field sound pressure is usually conceived as a fairly symmetrical "N" wave; so named because a plot of the shockwave pressure is a horizontal straight line before the arrival of the sonic boom, followed by a sudden sharp upward increase in pressure, a relatively slow downward decrease in pressure to below the original pressure, and a return to normal. The plot, therefore, looks like the letter "N," and the length of the "N" is directly related to the length of the aircraft. The nose of the aircraft produces a positive overpressure and the tail of the aircraft produces a negative overpressure. Estimating the intensity of "N"-wave overpressure is accomplished by a complex application of the area rule. An area-rule plot calculated in the conventional way is compared with one calculated from the Mach-angle cuttings related to lift. In effect, there is an area rule for frontal areas and an area rule for lift. When these are added, an effective area-rule plot is obtained. By comparing the curve of this plot with a series of parabolas, whose derivatives are straight-line segments and whose second derivatives are "pulse segments," an approximation of a second derivative function of the area-rule curve is obtained. This function is then integrated and becomes the major factor of the equation relating far-field overpressure to aircraft velocity. The entire procedure has been so arranged as to permit relatively easy machine computation.

The significance of the lift-area rule to sonic boom particularly applies to supersonic transports. It has little to do with flow itself when the lift function is absent. The minimum-sonic-boom concept is also discussed. Certain relationships of aircraft area and length will give a minimum sonic boom, although devices built on this basis alone would not necessarily be useful aircraft. These calculations show indirectly that minimizing one function probably maximizes the overpressure elsewhere, since the lift phenomenon is unsymmetrical; that is, the lift force is upward from the ground on which the overpressure will be noted. It is probable, therefore, that the overpressure above the aircraft may increase when there is minimum ground over-pressure.

In 1963, Carlson of the Langley Research Center presented a paper in which he reviewed the effect on sonic boom characteristics of configuration of the aircraft (ref. 58). Although the report emphasized aircraft structure rather than the acoustic aspects of the problem, the technical discussion should be of interest to investigators of sonic-boom phenomena.

McLean and Shrout presented a paper to the Acoustical Society in 1965 (ref. 59) in which the general area-rule problems of far-field sonic boom were reviewed. Up-to-date information on the importance of near-field sonic-boom overpressure was also discussed. Near-field effects were included because, in the case of slender aircraft configurations, the pattern of near-field overpressures might extend all the way to a distant ground, so that the classical "N" wave would not reach the ground. However, by modifying the shape of the aircraft, it could be possible to have the "N" wave and the ground wave so changed that a single-valued pressure wave, followed by a series of fairly weak tail waves, might occur. Progress has been made in reducing the total overpressure by these techniques.

From the viewpoint of a supersonic aircraft designer, the near-field phenomena may be useful not only to cope with overpressures at a distance, but also with those occurring relatively close when the aircraft is climbing. The acoustician is interested mainly in the detailed consideration of near-field phenomena, which are more important than far-field phenomena for nonaerospace applications of supersonic flow. On the other hand, because aerospace researchers have made more concentrated efforts in studying far-field sonic-boom effects, relatively little near-field work has been done in the aerospace field until recently.

Studies of sonic boom have produced some interesting laboratory techniques and analytical procedures that are of potential nonaerospace use. In 1959, Carlson and Langley Research Center described a wind-tunnel investigation of the sonic boom (ref. 60). Essentially, the study's objective was to confirm the theoretical analyses of supersonic overpressures by testing extremely small models in wind tunnels. The basic theory of Whitham (ref. 55) relating to supersonic overpressures generated by projectiles in flight, and the methods of Busemann (ref. 61) and Walkden (ref. 56) by which lift-induced pressures are estimated, were applied in the experiment. Of primary interest was the method of instrumentation that was devised to measure pressures at the orifices of a boundary-layer bypass plate, which consisted of a flat plate located in the airstream with orifices in its surface where pressures were to be measured. Theoretically, the plate had essentially no effect on the airstream and on the overpressure propagation. The measurements indicated that the method was accurate, but that some sound reflections at the plate, which should give a doubling of pressure at the reflection point, do not behave as anticipated. This phenomenon may be caused by boundary-layer effects at the plate.

In 1961, Carlson followed up this work with further experimentation (ref. 62). He extended the investigations described above and confirmed the lift portion of the theoretical overpressure equation with greater accuracy.

Further confirmation of the nature of the supersonic flow fields in the near-field region, which is of particular importance to nonaerospace application, is contained in another paper by Carlson, Mack, and Morris of Langley Research Center (ref. 63). This paper deals with theoretical analyses that were covered in other papers and verifies them with practical wind-tunnel measurements. The concluding remarks in the report are most significant, and are quoted:

> A wind-tunnel investigation of the supersonic flow fields about eight slender bodies of revolution has been conducted at Mach number of 1.26, 1.41, and 2.01. The investigation has shown that pressure-signature measurements taken at distances of up to 20 body lengths from the models are in good agreement with near-field theory and that values of the maximum-overpressure parameter are often much lower than estimates based on far-field assumptions. The result lends support to previous analytical studies which indicated that, for supersonic transport configurations in the transonic-acceleration portion of flight, airplane design could be modified to produce significant reduction in maximum sonic-boom overpressure.

> Even for very blunt-nosed bodies for which application of a theory based on slender-body concepts would appear to be questionable, near-field theory and experiment were found to be in reasonably good agreement. The blunt far-field lower-bound body had higher near-field overpressures than other shapes, but also had lowest measured pressure-signature impulse.

The reference to supersonic transport operation in this quotation is significant because the proximity of the transport to the measuring point includes the distance to airport surroundings during aircraft-climb-out. The near field, when scaled to smaller objects, is an important distance range. The lower bound refers to the artificially calculated body shape that produces the minimum overpressure without regard to its usefulness in designing aircraft with good lift and low-drag characteristics. This lower-bound shape is of interest to those who wish to minimize supersonic shock problems in nonaerospace applications.

In 1967, Hicks, Mendoza, and Hunton of Ames Research Center investigated the effects of Mach number on sonic-boom effects (ref. 64). Wind-tunnel and theoretical tests were used to evaluate the applicability of the Whitham sonic-boom-prediction technique for Mach numbers as high as 5.5. The study confirmed that the Whitham theory is quite accurate up to Mach numbers of about 3.0, but, at Mach numbers above 3, there is a rapid deviation between the theory and experiment. This is not surprising, since the original Whitham theory has a sharp Mach-number limitation on its validity.

In 1960, a technical note was prepared by Smith of Edwards Flight Research Center in which some experiments performed by flying supersonic aircraft at distances of 120 to 435 ft from pressure-measuring facilities were discussed (ref. 65). In this brief paper, the relationships between the various fields surrounding the supersonic aircraft were considered. The local field extends from the body surface to approximately the wing tips. Consideration of the flow in this region is important in determining effects of the interference that occurs between one airplane component and another component—effects that would occur in related applications in nonaerospace fields. The far field is that region where all the intermediate shock waves are joined and only the bow shock and rear shock remain. This flow has little applicability to the nonaerospace field. The near field is the region immediately beyond the wing tips of the airplane, where the intermediate shocks produced by the canopy and wings are of interest in determining the effects of close formation flying and aerial refueling operations. These effects are also of great interest to the nonaerospace acoustician. An earlier paper by Ferri (ref. 66) was cited for its applicability to the prediction of local-field flow characteristics. The methods of Whitham were found to be reasonably accurate in experiments conducted in both the near field and the far field. The conclusions of this study are of general interest:

> 1. The strength of the bow shock wave and the overall characteristics of the flow field can be estimated by using simple theory; however, the location and magnitude of all the intermediate shocks are not accurately predicted.
> 2. The normal area distribution (Ed. note: an aircraft design term) used in the theory may not be an adequate representation of an equivalent body of revolution for estimating the entire far-field flow, especially at Mach numbers much greater than 1. Using an equivalent body of revolution based on the area intercepted by parallel planes swept at the Mach angle greatly improved the results of the calculations. (Ed. note: This Mach-angle sectioning is derived from lift considerations.)

These conclusions together with those of other investigators establish that the lift phenomena are very significant in determining acoustic-flow fields. Lift considerations are so important for aircraft calculations that literature on supersonic flow phenomena that is developed for aerospace applications must be used with caution outside the field.

Many wind-tunnel tests have been made to relate local-field and near-field sonic-boom flow patterns to those measurable with practical aircraft flying at supersonic speed, and to extrapolate these patterns to the far-field sonic-boom-overpressure patterns, which are the most significant to supersonic flight. Because most wind-tunnel experimentation is limited, and the instrumentation often interferes with the nature of the test, a test program was set up to evaluate the feasibility of simulating the sonic boom by using ballistic models (ref. 67). The test program was designed both to select appropriate instrumentation to measure the pressure signature of small-scale rapidly moving ballistic models and to define problems associated with launching and flying winged ballistic models. The conclusions drawn from these tests are quoted:

> 1. Commercially available pressure transducers can provide . . . good quality pressure signatures resulting from shock-wave systems of ballistic models in flight. Measured maximum overpressures were, in general, higher than predicted theoretical levels, possibly due primarily to nonlinearity in transducer sensitivity.
> 2. Specially tailored transducers show promise of improvement in the quality of pressure signatures over those commercially available.
> 3. Motion of delta-wing ballistic models varied from a smooth type of flight to one of highly erratic oscillatory motion. Consideration of model tolerances, sabot design, and light-gas gun tolerances revealed no significant parameters which would lead to the allowance of any degree of repeatability of model flight paths. On those tests wherein model motion was of a non-oscillatory type, good shock wave pressure signatures were obtained.

4. Models launched into the ballistic range tank at reduced pressure exhibited a more acceptable type of motion.

5. Limited testing was conducted to explore the possibility of launching bodies of revolution at Mach numbers up to 5. Good quality pressure signatures were obtained.

Special tailoring of the transducers was considered desirable to develop sufficiently sensitive microphones to record transient wave forms produced by weak shock waves. Transducers for this purpose would be required to have such characteristics as small size for effective response at small orifices in surrounding surfaces, high resonant frequency for high-frequency response with good damping, adequate sensitivity, and linearity at maximum sound-pressure levels. Detailed development of this nature has considerable significance outside the aerospace field.

Two papers presented in 1965 at a conference on aircraft operating problems treat the sonic-boom problem as it relates to practical aircraft applications (refs. 68 and 69). They contain convenient reviews of methods of predicting sonic-boom pressure fields, and of the significance of the atmosphere and aircraft operations on sonic-boom exposures. The literature references are extensive in these papers.

An excellent general summary on sonic booms, how they are created, their effect on people and buildings, and their importance in the future is presented in an article written by Hubbard of Langley Research Center in 1968 (ref. 70). The mechanism by which the boom is created is discussed together with the "bow wave," the "tail wave," and the development of the characteristic "N"—shaped wave. The effect of altitude and atmospheric variability on the transmission of the sonic boom to the ground as well as the effects of sonic boom on buildings are discussed. In addition the relationship between sonic-boom effects on buildings and the occupants' subjective responses are analyzed. The article is an excellent overview of the entire subject in concise form, and provides an extensive list of references.

COMPRESSOR NOISE

The extraordinary refinement of the axial-flow air compressor has contributed significantly to the rapid development of the modern turbojet aircraft engine. The increased use of this device in conventional industrial fields has paralleled its application to aircraft but less spectacularly and with lower performance requirements. For example, the mechanical properties and temperatures required of aircraft engine compressor blades have taxed the capacity of modern technology, whereas a typical industrial compressor can be constructed of conventional materials.

Noise, however, is common to both aircraft and industrial compressors. Compressor noise may now be the principal source of aircraft engine disturbance to human beings. Studies of the origins of noise in aircraft compressors are almost directly applicable to the silencing of industrial axial-flow compressors. Aircraft engineers have developed these devices to such a level of performance that they are now displacing the piston compressor more and more in industrial applications. Axial-flow compressor noise reduction has therefore become industrially important. At the same time, industrial use of the fixed turbojet aircraft-type engine has necessitated the reduction of total-engine noise.

Many studies of compressor noise have been undertaken by NASA. These studies have considered not only the mechanism of noise generation, but also the propagation of noise in the jet duct of an aircraft engine, and its radiation from the face of the duct. Although the mechanical and mounting arrangements of compressors in aircraft may differ from those in industrial applications, the noise problems are similar.

An early NASA study dealt with the interaction of the rotor with the inlet-guide vanes as the primary source of noise generation (ref. 71). A 14.75-in. diameter single-stage axial-flow compressor was used in an anechoic test cell. A 52-hp variable-speed electric motor drove the compressor at rotor-tip Mach numbers of from 0.20 to 0.50. The test facility was so arranged that the number of inlet-guide vanes, the vane turning angle, and the axial spacing between the inlet-guide vanes and the rotor blades could be varied. The test rotor was mounted in a suitable rectangular air-flow duct, which terminated in a large open space below the floor level of the test cell. The compressor speeds ranged up to 145 rps, corresponding to a maximum tip speed of 560 fps. The test rotor was a single-stage axial-flow unit with 53 blades of a root diameter of 10.72 in. and a tip diameter of 14.75 in., which were taken from one stage of a multiple-stage, jet engine compressor. The rotor wheel was so modified that the blades could be set at the proper turning angle for maximum efficiency as a single-stage compressor. Tests were made without guide vanes, and with 31, 53 and 62 guide vanes in different test arrangements. The inlet guide vanes were obtained from the stator of the same multiple-stage compressor from which the rotor blades were obtained. Adjusting the turning angle of the guide vanes varied the rotor blade loading. The axial spacing between the guide vanes and the rotor was varied from 0.535 to 0.11 guide-vane chords by spacer rings.

Commercial condenser microphones were used at perpendicular incidence, around the radius of a 12-ft-azimuth circle, to obtain a noise survey pattern in a horizontal plane containing the center line of the inlet duct. The microphone signals were recorded on a multi-channel-FM tape recorder with overall system response of from 20 to 10 000 Hz. In addition to the microphones spaced at fixed 15° intervals, a continuous recording was made with a microphone that traversed the full range of azimuth angles. The recordings were played back to a graphic level recorder and a ⅓-octave-band analyzer.

Specially constructed pitot-static tubes were installed in the air flow upstream of the rotor and guide vanes to measure flow properties. The pitot-static tubes were equally spaced across the duct to feed pressure cells that provided electrical signals, the output of which were recorded on a multi-channel oscillograph. Additional pressure devices (yawmeters) were located downstream of the rotor to measure the pressure rise across the rotor.

This study was based on aircraft engine components, and was limited to considering a single stage of a multi-stage compressor in order to isolate effects. None of these specific provisions limits the application of the results to general industrial compressor noise problems.

The compressor was operated two to three min to obtain uniformity. Noise data together with the other operating parameters were recorded for each of the several test conditions. The accuracy of the pressure instrumentation was checked by calculating the total rate of air flow from the known characteristics of the rotor and was compared to the measured velocity distribution through the compressor.

In an analysis of this report, Tyler and Sofrin (ref. 72) have indicated that the noise generated in a compressor has rotating pressure patterns, called spinning modes, which may be generated by either a compressor rotor or a rotor-stator combination, with differing results. For the rotor alone, the pressure field consists of a single nB-lobed pattern which rotates with rotor angular velocity to $2nB$ (n=harmonic number, B=number of rotor blades, N=rotor speed in rps); consequently, an oscillating pressure is generated at a frequency of nBN Hz. For the rotor-stator combination, however, an impulse of pressure is developed as each rotor blade passes in the wake of a stator. Thus, many pressure patterns are formed, each of which has a number of lobes and a rotational speed that can be determined. Although the impulse at the rotor blade may be modified in amplitude and shape by the size and loading on the stator and by the distance between the stator vane and the rotor blade, it will have the same periodic recurrence.

Whether the pressure pattern propagates without a decrease in intensity to the end of the duct or decays along the duct depends on the speed with which it sweeps the duct's walls. The crossover point, or "cutoff" Mach number, occurs when the propagating mode sweeps the duct walls at sonic speed. The operating conditions for cutoff depend on the circumferential rotor-tip Mach number, lobe number, and the hub-tip ratio. The cutoff Mach number for the rotor alone is not attained until the rotor-tip speeds approach Mach 1. In these tests the cutoff Mach number was not reached. For a rotor-stator combination, however, it was found that pressure patterns having rotational speeds above Mach 1 could be formed even though the rotor-tip speed was much less than Mach 1. The cutoff ratios and the data from which they are calculated are contained in the report to indicate the conditions of decay or propagation.

The primary conclusions of the report indicated that, with the 53 guide-vane configuration, the maximum noise peak lay along the compressor axis and at the fundamental blade-passage frequency (6940 Hz). In every case, an increase in the tip speed resulted in an increase in noise level. For the rotor alone, and in combination with the 31 and the 62 guide vanes, the radiation patterns were nearly circular, whereas for the rotor in combination with the 53-guide vanes, the peak noise level was on the 0° azimuth. An analysis of the calculated and measured radiation patterns revealed that the calculations indicated fairly accurately the direction of maximum radiation and the number of lobes in the patterns. They did not, however, predict the detailed lobe structure of the pattern, nor the radiation in the direction of the axis of rotation, although the experimental results indicated a considerable pressure in this direction.

For the 31-guide-vane assembly, measured and calculated radiation patterns were in considerable disagreement. The calculated pattern had a simple maximum at 90° azimuth, whereas the experimental pattern was multi-lobed and the measured peaks were not in the calculated direction. The differences in pressure patterns for the rotor alone compared to the inlet-guide-vane-rotor combination indicated that the interaction between guide vane and rotor is of considerable significance. Therefore, the effects can be expected to differ sharply with the axial spacing between the guide vanes and rotor.

The general conclusions of the overall study indicated that:

1. The noise radiation patterns of the tested compressors were nearly circular in shape, and the radiation patterns at the blade-passage frequency exhibited lobes. The number of lobes was dependent upon the inlet-guide-vane-rotor configuration; that is, the number of vanes and the rotational speed.
2. The calculations enable the qualitative determination of noise radiation patterns that are in agreement with experiment in the range for spinning modes above cutoff Mach number; that is, in the range for propagation. However, in the range below cutoff (in the range of decay), the experimental and calculated noise-radiation patterns have little similarity.
3. A change in guide-vane loading, with a resulting change in rotor-blade loading, has an effect on the noise-radiation patterns when they are analyzed at the blade passage frequency; but such change has little effect on the patterns at constant rotor-tip speed.

In a study conducted at Langley Research Center, the work described above was extended to include downstream interaction phenomena (ref. 73). Under essentially identical experimental conditions as those used in the preceding reference, noise measurements were conducted for the rotor alone, and for such combinations as the inlet-guide vane-rotor, the rotor-stator, and the inlet-guide vane-rotor-stator. The stator is a downstream stator of 62 vanes, very similar to the inlet-guide vane. This study concluded that radiated-noise levels generated by the interactions of rotor and downstream stator vanes are appreciably less than those caused by inlet-guide vane-rotor interactions. Noise reductions can result from increased inlet-guide vane-rotor spacing and can be further increased with the addition of the downstream stator. As before, however, these changes in noise radiation were measured at the blade-passage frequency, and no significant effect of the downstream stator was observed on the overall noise level.

In a related but earlier study, the effect of the geometry of a jet engine on generated noise radiation was investigated (ref. 74). The inlet-duct configuration that was examined in this study had modified duct lengths and added duct resonators. The experimental arrangement involved a 20-blade rotor, with a 24-in.-root diameter and a 34-in.-tip diameter, which was rotated by a variable speed electric motor operating up to 110 rps, corresponding to a maximum rotor-tip speed of 980 fps. No stator was used in this experiment. Modifications in the duct geometry upstream of the rotor involved changes in duct length between the inlet and the rotor plane of from 4 to 16 ft, and the addition of an input resonator of 4-ft duct length. The resonator, basically a tuned Helmholtz resonator, was designed for maximum effectiveness at 70% of the compressor rotational speed. The test was conducted outdoors, far away from reflecting surfaces. Commercial-type condenser microphones, having a usable frequency-response range of from about 5 Hz to 10 kHz, were spaced at 15° intervals of azimuth. Additional tests were made with a microphone that was moved continuously in azimuth. Static- and total-pressure measurements were made with static-pressure taps and a total-pressure rake connected to a multitube manometer. This instrumentation was photographed during the test.

The test revealed that, by increasing the duct length from 4 to 16 ft, the overall noise level was reduced by 7 dB, and the noise level at the fundamental blade-passage frequency, by 10 dB. Reduction of up to 4 dB in overall noise, and up to 10 dB at the fundamental blade-passage frequency, were obtained by using an inlet resonator at the designed rotor-tip speed. For all inlet configurations, the overall noise-radiation patterns were found to be nearly circular, whereas discrete-frequency noise exhibited lobes. The spectra of the overall noise contained two broad noise peaks in the vicinity of 100 Hz and from 1 to 3 kHz, and there were some discrete-frequency harmonics of the blade-passage frequency. The time histories of the discrete blade-passage-frequency noise exhibited amplitude modulation similar to that noted for other single- and multiple-stage axial-flow compressors.

NOISE SUPPRESSION

Most of NASA's work on noise suppressors for turbojet aircraft engines was completed soon after NASA was established, since it was essentially an extension of programs initiated by NACA. Early interest in the exhaust type of noise suppressor declined when it became apparent that the turbine whine was of greater significance as a source of perceived noise, but two papers of significance were produced by NASA on noise suppressors in the period up to 1961.

In 1959, an investigation of exhaust noise from rectangular slot nozzles having a wide range of height-to-width ratios was accomplished by Coles of Lewis Research Center (ref. 75). In this study, the primary method used to suppress aircraft noise was that of mixing a large volume of air with the exhaust jet stream and spreading the turbulent exhaust mixture over as large an area as possible. This type of suppression essentially reduces the local intensity of pressures associated with turbulence that generates noise. Although many different ways of mixing and spreading nozzles had been tried, the regular multi-lobed configuration appeared to be the most effective with conventional turbojet aircraft engines. The interest in a slot nozzle or one with a relatively high length-to-height ratio probably developed with increased attention to developing STOL/VSTOL aircraft. Designs of such aircraft specified the employment of jet exhaust; either by forcing it against flaps to affect the control of the aircraft, or by directing it downward by flaps to alter the course of the engine thrust into a direct force. Obviously, a long rectangular-nozzle configuration is more amenable to such an application than the cylindrically symmetrical output of a multi-lobed flower-like noise-suppressor nozzle. Figure 11 indicates that the range of ratios of length to height was fully investigated; at least one of the experimental nozzles appears to be almost as wide as the wingspan of the fighter aircraft used as the noise source.

It was concluded in the report of this investigation that the noise-suppressing capacity of the slot nozzle is confined primarily to changes in the directivity and frequency of the noise. It was both predicted by theory and demonstrated in the experiment that the actual reduction in acoustic output is slight (3 dB). The directional changes in the noise distribution were observed to be significant, but the sound levels on the ground, either directly under or to the sides of the flight path of the aircraft equipped with a slot nozzle, were not particularly affected. The reduction in noise at the azimuth directly aft indicated a reduced duration of the highest noise levels along the immediate sides of the flight paths. The slight tendency for the frequency distribution of the noise to move toward high frequencies assisted in some instances the atmospheric attenuation of the noise, but possibly produced an effect more objectionable to the listener. The addition of the

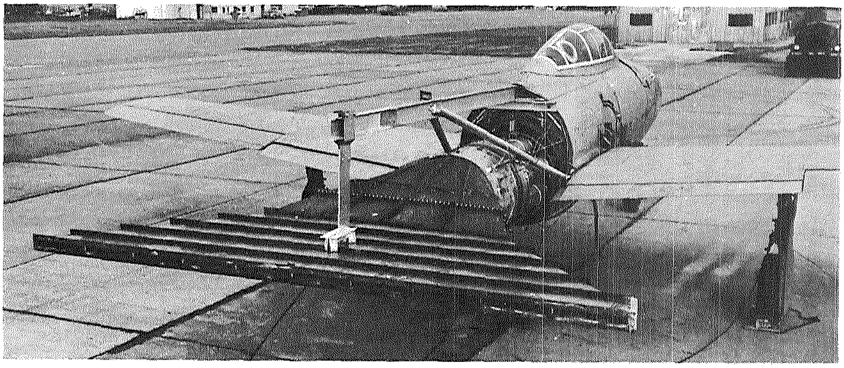


FIGURE 11.—Slot nozzle, 100:1 width-to-height ratio.

flaps to the slot nozzle considerably reduced the sound level. It was suggested that flaps of longer chord would be more satisfactory than those tested, and that a compromise chord length might give an optimum result.

A more general discussion of practical suppressors of jet aircraft exhaust noise is contained in a research report by Coles, Mihaloew, and Swann of Lewis Research Center (ref. 76). The action of noise suppressors which operate by spreading and mixing the turbulent jet with the surrounding atmosphere is described. The principles involved in this type of action may be applicable in other turbulent-noise-suppression fields. The test vehicle was a B57B which has the jet engine located in the wing. A relatively long tail pipe leading to the exhaust nozzle was required, and the wing had to be protected from the extreme temperatures of the engine by the injection of cooling air around the exhaust pipe. This type of arrangement is found in relatively few aircraft, but it may represent many industrial situations where jet-type turbulence is encountered. The two types of suppressors utilized in the experiment had eight-lobed flower-like nozzles with which rather elaborate arrangements were needed to inject the cooling air. In the absence of cooling air injectors with conventional round nozzles, a complex fairing was placed around the eight-lobed nozzle with an arrangement for cooling air to be injected between the fairing and the nozzle. This assembly comprised the basic suppressor; a second version included a so-called noise-suppression ejector (fig. 12). The ejector was essentially an annular ring, having an airfoil cross section, located just aft of the nozzle. The ring concept provided airfoil action to inject and mix more air into the exhaust stream, thereby reducing the noise. Such an ejector ring can also be used to aug-

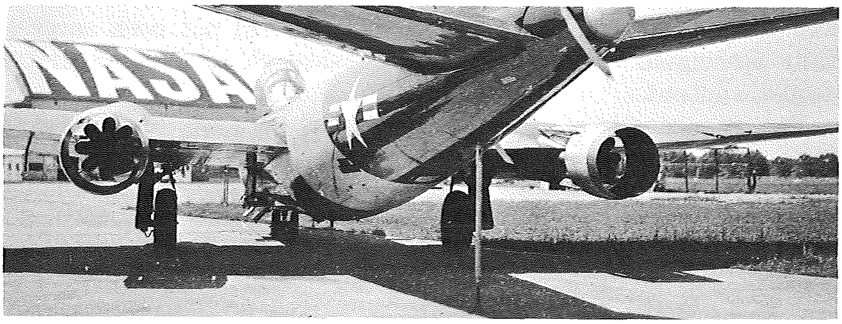


FIGURE 12.—Noise suppressor and ejector.

ment the thrust under certain circumstances because of the airfoil effect of its cross section. However, an ejector designed to mix the maximum amount of noise-suppressing air could not give a thrust increase.

The conventional instrumentation of fixed ground tests and flyby airborne tests is described in the report. It was concluded that the lobed type of noise suppressor used in this experiment reduced the sound pressure levels as much as 5 dB, and the radiated acoustic power by 3 dB for ground operation at high engine power. The addition of the noise-suppressing ejector essentially doubled the static noise reduction. All these reductions occurred at frequencies below 2 kHz, with the higher-frequency range essentially unaffected. Loss in static thrust directly attributable to the suppressor nozzle was approximately 3.5%, part of which was regained by the action of the ejector. In flight, the suppressor nozzle reduced maximum sound pressure levels under the flight path by over 6 dB, and reduced the perceived noise levels by 5 to 6 dB. The ejector provided no significant improvement in the noise characteristics.

The evaluation of flight performance indicated 3% and 7% increases in the drag coefficient for the suppressor and the suppressor-plus-ejector, respectively. The loss in specific range resulting from this increase in drag varied from 5% to 7.5% at both 15 000 and 25 000 ft for the suppressor, and, for the suppressor-plus-ejector, from 8% to 11% at the lower altitudes, and from 11% to 14% at the higher altitudes. The improvement in acoustic characteristics during static operation realized by using the ejectors was considered insufficient to justify the complexity and the performance penalty associated with its use. A transient noise phenomenon, which is known as the tearing effect, appeared to be associated with high-amplitude fluctuations, predominately in the 400- to 2500-Hz band. The periodicity of this phenomenon approached that of a triangular wave. Although the phenomenon had often been noted in previous tests, it had not been successfully associated with any specific physical characteristics of the acoustic output.

The nonacoustic effects of noise suppressors are considered in two other studies; one by Laurence of Lewis Research Center (ref. 77), and the other by a group of investigators at Langley Research Center (ref. 78). The study by Laurence deals with the turbulence generated by an unusual type of slotted noise suppressor. The investigator's purpose was to examine the effect of the suppressor-generated turbulence on the total jet turbulence. The Langley study is an investigation of what happens to aircraft performance when suppressors for acoustic purposes are employed.

As the size of boosters for space vehicles was steadily increased, it became apparent to workers in the field that the amount of noise created by such boosters might become almost unmanageable. Successively larger boosters generated increasingly louder sound outputs, and by 1962, it was considered probable that the Saturn V booster might create so much noise that the Marshall Space Flight Center might have to be evacuated during tests, and that damaging acoustic levels might be produced over considerable distances if atmospheric sound-focusing occurred. For this reason, several booster sound-suppressor structures were designed and scale models were tested. No full-scale booster sound suppressor, however, had been constructed prior to the first static test of a Saturn booster. It was discovered that, although test sound levels were in many ways as high as had been predicted, fairly straightforward precautions could prevent them from causing serious trouble. Furthermore, the development of better methods of predicting anomalous long-distance sound transmissions from atmospheric measurements increased the confidence of acousticians in dealing with the problem. It became evident that unexpectedly intense sound levels over long distance could be prevented by simply cancelling tests when the probability of anomalous propagation was high. Consequently, no full-scale booster sound suppressors were built, and the suppression of noise in such large boosters no longer appeared so important.

Nevertheless, suppression methods and construction and testing of scale-model suppressors may be of interest in other fields. Dr. Fritz Kramer of Marshall Space Flight Center made a study of predictable acoustic performance of the S–1C sound suppressor (ref. 79). This suppressor was a device that forced the exhaust gas of the booster downward into a pool of water through which the gas was deflected slightly upward to a final path along a horizontal line at right angles to the exhaust direction. The entire structure, including the deflecting passage and the horizontal "run-out" area, was filled with water (fig. 13). Theoretical studies have indicated that the addition of a large amount of water to the exhaust gases reduced their velocity, and, consequently, the sound by amounts on the order of 20 dB.

In this paper, the performance of 1/7-scale and 1/20-scale models of the sound suppressor is discussed, and the performance of a full-scale suppressor is predicted. Based on both theory and experiment, it is established that for one of a pair of dynamically similar sealed systems (see ref. 80), the sound-pressure spectrum

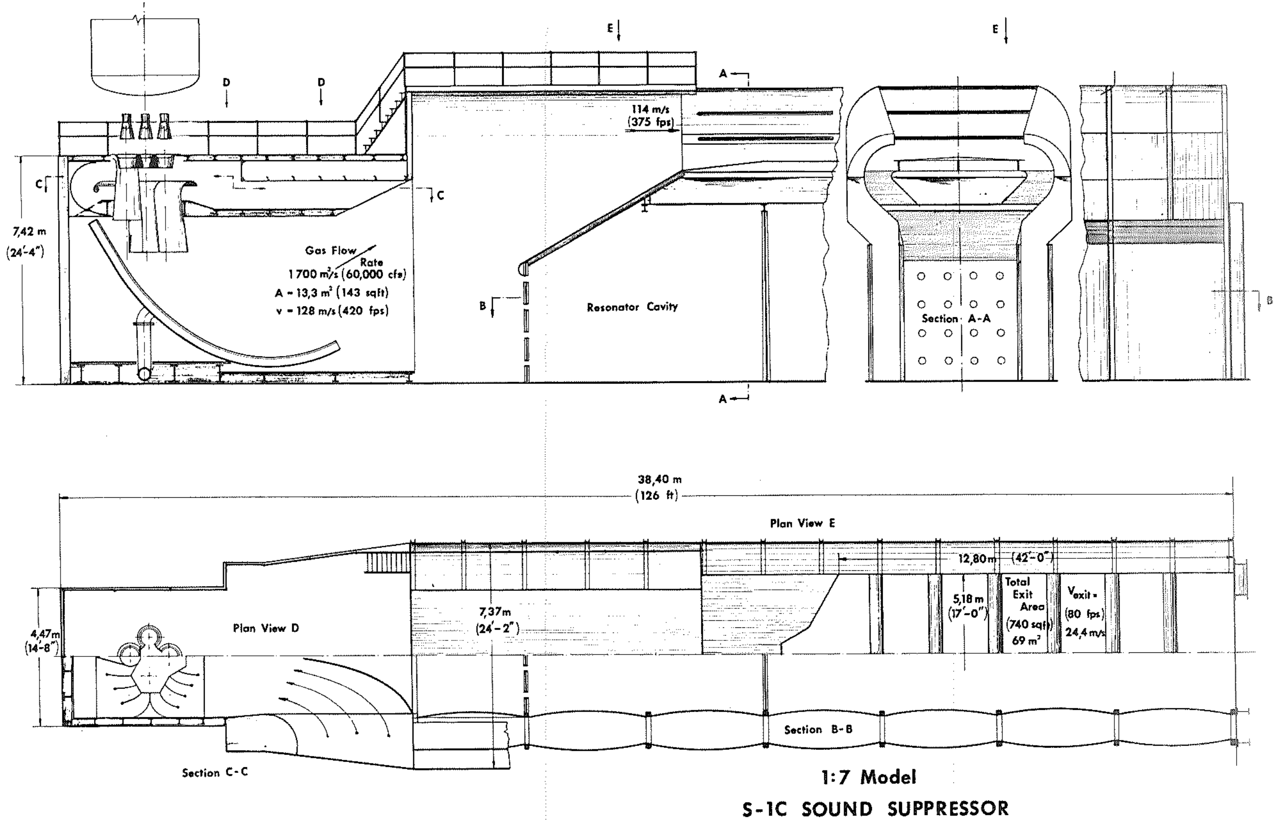


FIGURE 13.—Longitudinal cross section through the 1:7 scale model sound suppressor.

measured at one position on one system was the same as that measured at a similar position on the other system in the same frequency band, if the frequency is scaled inversely proportional to a characteristic length. This leads to a dimensionless frequency parameter, defined by frequency times a characteristic dimension of the system (such as the engine-nozzle diameter) and divided by a characteristic velocity. The model and the prototype rocket engines have the same specific impulse and exhaust velocity. If the same conversion efficiency is assumed for the model and the prototype, it follows that the overall sound pressures measured at geometrically similar points are the same, and that the sound pressure is scaled according to the thrust ratio (or λ^2, where λ is the dimensional scaling factor), based on the fact that the total power is directly proportional to thrust. To scale sound power:

1. The octave-band sound power spectrum must be shifted in frequency by a ratio of $1/\lambda$.
2. The individual power level must be increased by the addition of $10 \log (\lambda^2) = 20 \log \lambda$ dB.

In this case, the total thrust source for the five F-1 engines used during the test was 7 637 000 lb-ft. This value was used to determine the actual model scales and the proper value for scaling the model acoustic-power levels.

Various problems of scaling and estimating the sound levels of systems, and the results of a specific engine test (fig. 14) are discussed in this paper. The figure shows the octave-band sound pressure levels measured in a full-size engine test (S–1C–08, performed on 11 June 1965) and the predicted results for similar tests that might be performed with a 1/20-scale model and a 1/7-scale model. The goals established for the suppressor included reduction of the sound level below 110 dB at 2.6 miles in the low-frequency region, since low-frequency propagation always appears to be greater than theory might indicate, and sound energy in a high-thrust booster tends to concentrate in lower frequencies. In addition, the lower frequencies can be expected to cause greater human annoyance.

Discussions of problems relating to the construction and operating stability of such suppressors are also included in the paper. Two other reports on these subjects were developed concurrently for NASA in 1966 (refs. 81 and 82). The difficult problems of stability that occur when a thrust of seven million lb is dumped into a mass of water contained in a reservoir several hundred feet long are considered in these papers. Certain aspects of hydraulic engineering are involved as well as those pertaining to acoustic engineering.

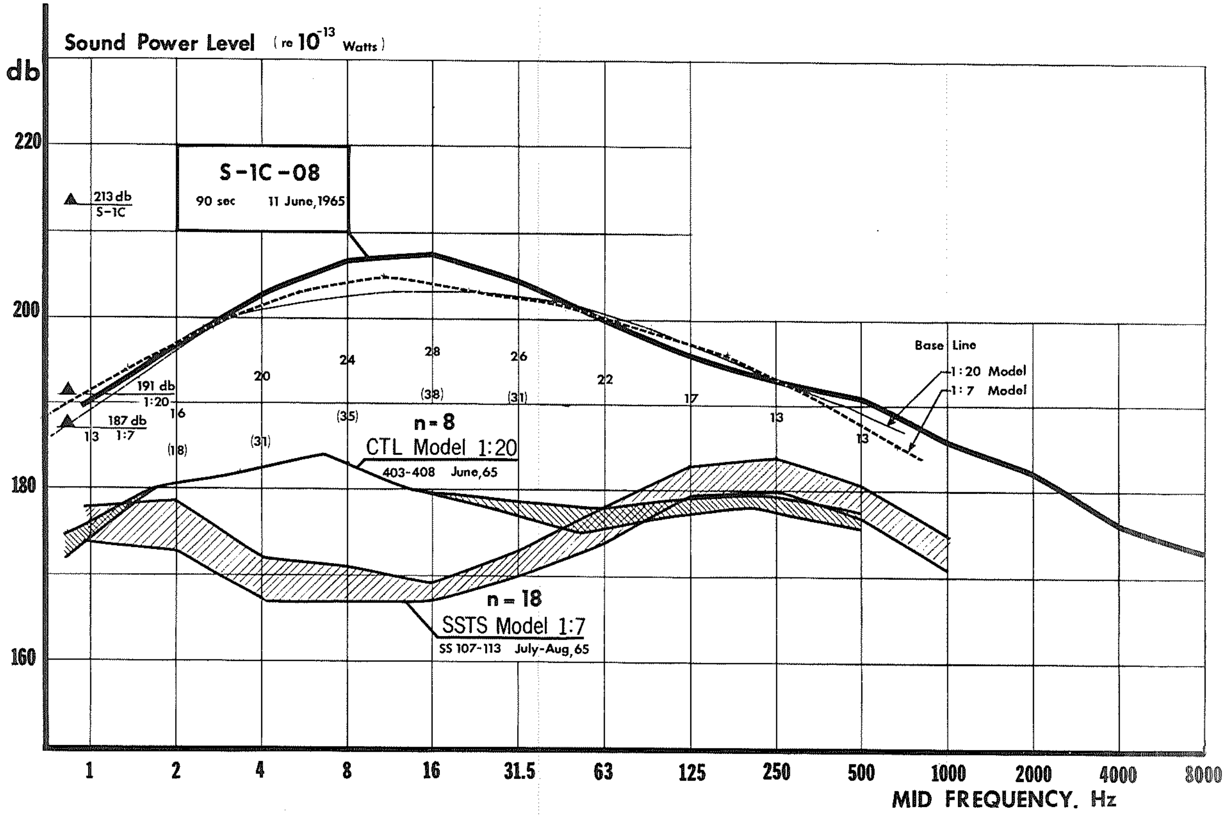


FIGURE 14.—Acoustic performance of the S-1C sound suppressor as the scaled-up model performance.

Aircraft engine noise may be reduced by choking the input to the turbojet engine. This is achieved by placing within the input-air opening a streamlined obstruction so constructed and proportioned that the input air is throttled down and forced to flow at supersonic speeds as it passes the choke. By forcing the air to travel supersonically, internally generated noise is prevented from flowing out through the inlet opening of the engine. This technique should be particularly effective in reducing compressor noise radiation, since this type of noise appears to radiate in a forward direction. A study of this technique and its effectiveness is described by Cawthorn, Morris, and Hayes of the Langley Research Center (ref. 83). In this investigation care was taken to assure that this noise reduction technique would not seriously degrade engine performance. Consequently, much of the report deals with engine performance which has relatively limited applicability outside of aerospace technology. No increase in vibration of the test engine with the inlet choke was observed, and no erratic engine behavior was noted when the inlet was rapidly unchoked; however, some engine-performance losses were incurred at the lowest speed at which the inlet choked, and these losses increased rapidly as the engine speed was increased above the choking speed for each center-body location. Obviously, engine speed must reach a certain level before the inlet-flow rate is sufficient for the choke to cause supersonic flow in the choked region. For any particular location and geometry, therefore, there is a minimum of choking speed. It was also established that, for any position of the center body at which the inlet could be choked, choking occurred at a total pressure-ratio value of approximately 0.93. This value is the ratio of the pressure at which some point in the supersonic flow region has a fraction of the pressure at the outlet of the jet.

The noise measurements obtained indicated that choking the input flow was beneficial in reducing the noise levels forward of the engine. Reductions of from 2 to 5 dB were observed in the overall noise levels, whereas reductions of from 2 to 20 dB were noted in the noise levels of the fundamental blade-passage frequencies, the smaller reductions occurring from azimuths of from 45° to 90°, and the larger reductions occurring from the 0° to about the 45° azimuth. Blade-passage frequencies were more sharply attenuated than the overall roaring turbulence noise. Because of this improvement, it may be possible that the same choking principle can be used effectively in the bypass passage of a turbofan aircraft.

CHAPTER 3

Acoustic Propagation

NASA's main interest in sound propagation has been concentrated in studies leading to predicting the probability of sound energy returning to the ground at a point remote from the source of the sound. It is important, for example, to be able to predict whether a large spacecraft booster test will cause major acoustic disturbance to the population. However, many other aspects of propagation have been studied, many of which have nonaerospace applications.

This section of the Survey covers first conventional sound propagation and then deals with progressively more complex disturbances. The process by which the unwanted return of sound to the ground by atmospheric refraction can be predicted is discussed. This technique is useful in scheduling large booster rocket tests to ensure minimum disturbance. Finally, there is a discussion of acoustic propagation properties as useful measuring tools for such diverse applications as wind measurements and the determination of the amount of liquid in a liquid/vapor mixture.

CONVENTIONAL ATMOSPHERIC PROPAGATION

Because large rocket boosters of space vehicles produce noise primarily at low frequencies, techniques are needed to measure sound levels of less than 1 kHz that are absorbed in air, so that the acoustic consequences of booster tests and space flights can be predicted. Prior to the space program, there was little information on absorption of sound in this frequency range due to lack of interest. Relatively early studies on low-frequency sound absorption were conducted at Columbia University as recently as 1963 and 1965 (refs. 84 and 85).

Further studies of the propagation and absorption of sound, specifically in relation to temperature and humidity, were conducted by the same researcher in 1967 (ref. 86). Measurements were made of the absorption of sound in air at third-octave frequency intervals of from 2.0 kHz to 12.5 kHz as a function of humidity at six temperatures in the range from −25° to 25.1° C and at normal atmospheric pressure. These results were compared with those of past investigations to determine their validity, and then were extrapolated downward in frequency to 125 Hz, and in temperature over a range of from −10° to 30° C.

In reference 85, the experimental arrangement and measurement techniques are described in detail. Briefly, the attenuation coefficient of sound in air was evaluated in terms of the decay rate of sound diffusion in a spherical chamber 1.68 m in diameter. During measurements, the temperature of the chamber was held constant to within ±0.1° C, and precautions against contamination of chamber were accomplished by evacuating it with a vacuum pump. The spherical chamber was then filled with air having a carbon-dioxide content of 300 parts per million. Random noise from a source in the chamber was picked up by a microphone, amplified, and fed through a third-octave filter to a high-speed level recorder. When the random noise source was turned off, a sound-decay curve in the chamber was obtained. The slope of the curve determined the decay rate in dB/sec at the frequency of the center of the band to which the third-octave analyzer was set. For a single test condition, three decay curves were superimposed on each other, and the average of the three curves was obtained to determine the decay rate for this condition. This rate, when corrected for losses at the boundaries of the chamber, became a measure of the total absorption of sound in the chamber. In order to determine the rate of decay caused by losses at the boundary of the chamber, the boundary loss was measured directly. To do this, the chamber was filled with purified dry nitrogen, which exhibits no anomalous absorption in the measured frequency range. The observed rate of sound decay in the nitrogen-filled chamber and the value computed from absorption data on nitrogen represents the amount of decay attributable to wall losses. Detailed tables in the report should be useful for the reader who is interested in exact values of atmospheric absorption with humidity and temperature.

Whereas the papers discussed above dealt with the behavior of sound under normal conditions, the next study of propagation-related properties is concerned with very extreme conditions. An approximate model of air in equilibrium was established in 1959 by C. F. Hansen (ref. 87). Hansen, in collaboration with another investigator, later presented a tabulation of the computed properties of his approximate model of air for values of the dimensionless entropy, ZS/R, from 25 to 100, and for temperatures up to 15 000° K and pressures up to 1000 atmospheres (ref. 88). Because of the importance of isentropic flow in many fields of technology, entropy is included among the independent variables. With these variables, iterations of analytical approximations can be computed to determine thermodynamic properties as functions of entropy. The tabulation in the report includes the temperature, compressibility, enthalpy, specific heat, speed of sound, and the integral of acoustic admittance (i.e., the inverse of the product of density and the speed of sound) as constant-entropy functions of pressure. The technique used to obtain the tabular data in adequate detail for the range of variables is explained. The report is a useful basic reference for dealing with compressible-fluid-flow problems, particularly those dealing with high-temperature flows in high-speed flight and related industrial processes. The thermodynamic state relationships are complicated because the air molecules are excited simultaneously in vibration, disassociation, and ionization reactions. Previous investigators have made tabulations of some of the equilibrium thermodynamic properties of air and others have presented the results of the tabulations in a form of the Mollier diagram. The tabulations of this report are prepared as a supplement to the Mollier diagram. The speed of sound is included as a property involving many other properties, which makes the tabulations directly useful to the study of acoustic phenomena under extreme external conditions.

To understand the complications of the undisturbed propagation of sound, the refraction of sound waves must be considered. The University of Toronto has investigated extensively the refraction of sound by jet flow or jet temperature (ref. 89). Interest in this subject was stimulated by the heart-shaped directional pattern of jet noise (fig. 15). Although many conflicting explanations of this pattern can be found in the literature, one of the most promising contends that the intensity minimum is due to the refraction of the aerodynamically generated sound by the jet velocities and temperatures. In other words, the sound is created by the turbulence in a jet, and, in turn, is refracted by the jet itself. Exact analytical approaches to this problem are extremely difficult because the wavelengths typical of jet noise are large compared with jet dimensions. Therefore, any use of ray tracing must be suspect because conditions do not duplicate those of the actual turbulent jet. An experimental approach, therefore, was used in this investigation in which a harmonic point source of sound was placed within the flow field of a ¾-in. air jet, and the distortion of the inherently omnidirectional sound field of the point was observed. Four experimental parameters were considered of greatest importance: the jet velocity, the jet temperature, the source frequency, and the source position. It was found that the sound pattern of the harmonic point source was distorted compared with the pattern expected; that is, there was a dimple or valley in the pat-

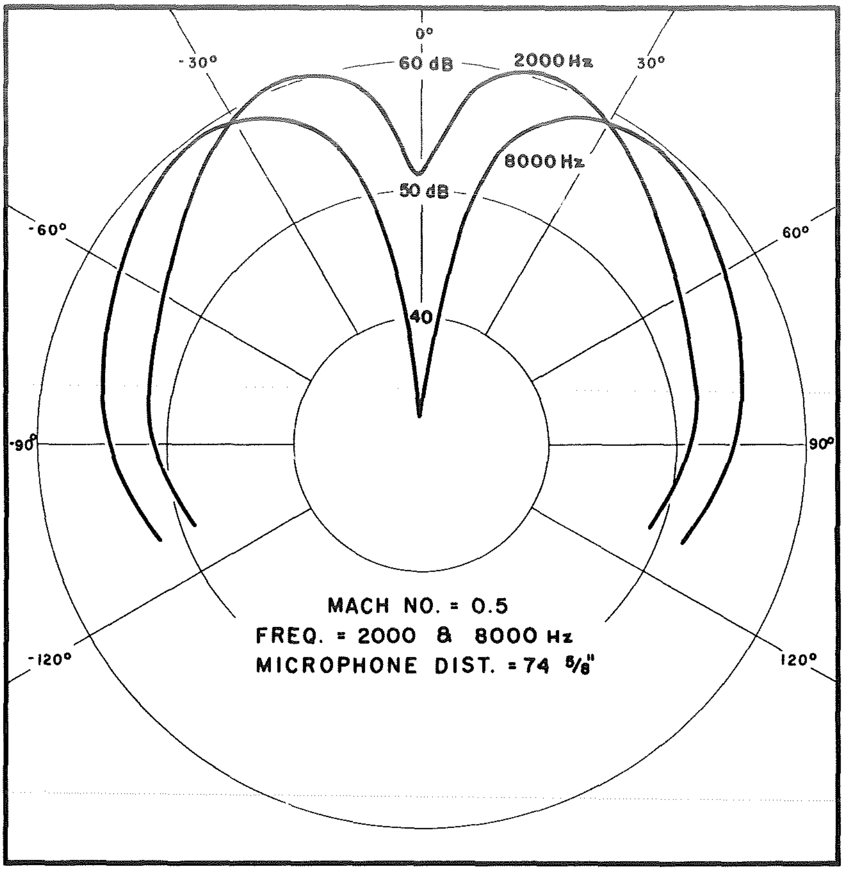


FIGURE 15.—Jet noise directivity for ¾-in. air jet.

tern along the direction of jet flow. Refraction was the main effect observed. The valley and the directivity patterns were the result of the sound ray bending away from the axis and out of the flow. The valley depth increased with jet velocity, jet temperature, and sound frequency in accordance with theory. This valley behavior in this experiment was similar to that observed with noise generated by jet turbulence, and the original thesis of the study, therefore, was substantially supported.

The refraction of sound waves by specifically defined discontinuities having been discussed, sound-wave diffusion by random processes in the medium will now be considered. The fluctuation of acoustic signals in media of randomly varying indices of refraction has been considered by many researchers having almost as many different points of view. On the basis of geometrical or ray acoustics, Bergmann and Obukhov (refs. 90 and 91) have studied the fluctuations in phase and amplitude of a spherical acoustic wave emanating from a point source. Skudrzyk (ref. 92) has also evaluated these quantities and obtained the probability distribution of the signal from a geometrical-scattering point of view, and has tabulated the results. Mintzer (refs. 93 to 95), using single- and double-scattering formulations, also calculated similar quantities. Obukhov's approach has the great advantage that he was able to obtain both Mintzer's and Bergmann's results as limiting forms of a single derivation. Lyon proposed to solve somewhat the same problem from a multiple-scattering point of view by formulating the transport equations for the acoustic-energy-density spectrum in turbulent flow (ref. 96). The diffusion was observed to take place both in frequency and direction, since the flow varies in time as well as space. The directional diffusion of a sound wave had been previously considered by Lighthill (ref. 97) who proceeded from a diffusion equation which apparently had been inspired by random-walk considerations.

Lyon derived a diffusion equation and then solved it with a rather complex resultant (equation 38), which reduces to Lighthill's results for time-independent scattering. Some of the author's concluding remarks will indicate the validity of the derivation:

> The Lighthill and Kraichnan scattering formulae are valid when the Mach number of the turbulence is low ($<< 1$). In addition, it will generally be true that the sound particle velocity will be small compared with the turbulent fluctuation velocities. This means that the sound-turbulence interaction is assumed larger than the nonlinear acoustic effects. The sound generated by atmospheric turbulence usually will have frequencies much lower than those which are of interest in propagating through the atmosphere. The interaction of scattering phenomenon may then be considered to predominate in the audible frequency range.

In evaluating the equation solution the author assumed that the acoustic wavelength was very small compared with the size of the turbulent eddy. This restriction was not too severe since the scale for atmospheric turbulence is usually fairly large, approximately equal to the height above ground. In addition, however, it was necessary that the scattering volume have large dimensions compared to the scale of the turbulence itself, which means that the propagation distance should be large compared to the scale of turbulence. With these restrictions, the transport-diffusion treatment of propagation in an isotropic turbulent atmosphere was found useful to predict the frequency spectrum and angular distribution of the sound-wave fronts in a probabilistic sense. The frequency distribution was interpreted as a power spectrum and the autocorrelation of the waveform was obtained by spectrum inversion. Unfortunately, the phase information was lost in the analysis. It is significant to note that, because the measurement of rapid temperature fluctuations in the atmosphere is still in a rather rudimentary state, the effects of thermal scattering, which must occur when atmospheric turbulence mixes regions of different temperature, have been omitted in this report.

A corollary of the effect of diffusion in a fluctuating medium is the scattering of sound waves by physical objects. A mathematical analysis of the extension of the principle of point matching, which is now widely used in engineering investigations of scattering from bodies of revolution, has been developed by Yee of the University of Alabama Research Institute. In this study, it is revealed that the methods of point matching used in two-dimensional engineering problems can be applied to three-dimensional investigations of figures of revolution (ref. 98).

In typical two-dimensional characteristic-value problems investigated by point matching, a finite number of points around the periphery of the boundary in question are chosen in such a way that these points describe the boundary contour (refs. 99 and 100). By utilizing a computer, this method can be applied easily to obtain many eigenvalues for the practical solution of similar types of boundary-type problems. For example, all hollow-pipe waveguide problems, within certain limitations, can be solved by the same computer program. In the case of typical three-dimensional problems, however, many more points are necessary to describe the surface of the body under consideration, and the large number of algebraic equations required in their solution may be beyond the capacity of present computers. This difficulty can be overcome for rotationally symmetric bodies which are frequently encountered in practical applications. In the referenced documents, the significance and utility of the analysis is described. A specific example is given to show the relative simplicity of application of the method.

COMPLEX ATMOSPHERIC PROPAGATION

To increase the understanding of sound propagation in atmospheres of complex (layered or partially layered) structure, and hopefully to develop a wind-measuring technique, the research effort known as the Rocket Grenade Experiment was undertaken. A report by Schellenger Research Laboratories of Texas Western College deals with the ground support, data analysis, and associated research development effort involved in this experiment (ref. 101). The experiment consisted essentially of firing rockets high into the atmosphere and exploding grenades at the rocket as it rose. The sound received from these grenades was recorded at widely separated points over the earth. The arrival times and wave shapes of these recorded grenade-explosion sound pressures were then analyzed and interpreted to construct a picture of the structure and wind velocity of the region through which the sound had travelled. Although the atmospheric-structure findings of the experiment are not of major importance in this survey, some of the instrumentation and subordinate findings in acoustic propagation are of considerable interest. It was observed that the wave shape of the acoustic signals from any single explosion had the "N" wave shape characteristic of the sonic boom. In sonic booms caused by aircraft, the "N" wave is considered to result from a wave from the bow and another from the tail of the aircraft, but the wave shape of the rocket grenade cannot be explained on this basis. The explanation offered in the report is that the explosion is so intense that a perceptible difference occurs in the velocity of propagation of the compression and of the following rarefaction thus creating the sound signal. Although such "N" waves from a single explosion had not previously been observed experimentally, DuMond and others predicted such waves based on theoretical considerations in 1946 (ref. 102).

The characteristic "N" shape is thought to result from the effect of a finite amplitude on propagation. Unlike the small-amplitude case, the speed of the sound wave is dependent on the amplitude above a certain level. Thus, the regions of overpressure (in front of the wave) travel faster than the average sound speed, and the regions of underpressure (at the rear of the wave) travel slower. This phenomenon causes initially rounded types of wave shape, having both overpressure and underpressure regions, eventually to acquire the "N" shape. This is illustrated in figure 16, point 1 travels faster than the local sound speed (which is the speed of point 2), whereas point 3 travels slower. As time passes, the wave shape shown in B is formed from that shown in A, and eventually the wave will stabilize with the "N" shape of C. In the actual physical case the compression of the atmosphere caused by the shock wave is irreversible, and the final pressure of the medium, after the passage of the "N" wave, is lower than the original pressure (ref. 103). The medium returns to its original ambient value asymptotically long after the passage of the wave.

The Rocket Grenade Experiment was an attempt to gain information about upper atmospheric conditions, including wind direction and velocity, by recording at widely dispersed points the arrival time of the sound from a series of explosions. Although it

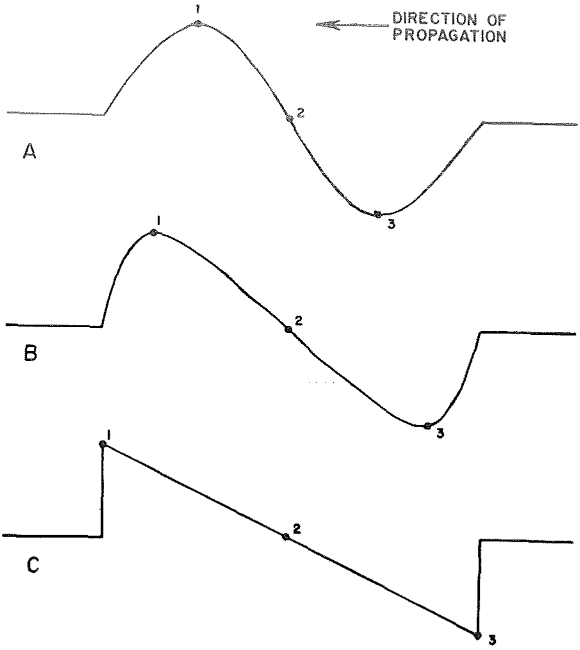


FIGURE 16.—Creation of "N" wave from a single explosion.

was not entirely a NASA experiment, NASA facilities were used for ground instrumentation in its support. A related but quite different technique was developed for the same basic purpose as that indicated above, and is described in reference 104. This technique involved the use of the continuous sound generated by a large booster rocket rising into the atmosphere. In this experiment, differences in arrival times of a particular part of the continuous noise output of the rocket exhaust were identified by cross-correlation methods, even though there were no distinctive explosions that could be separately identified. This procedure proved to be quite satisfactory. The wind measurements made with this technique during the flights of several Saturn vehicles correlated well with concurrent measurements made at lower altitudes. They also appeared to be consistent with atmospheric-circulation observations made at higher altitudes. The basic problem in using most current wind-measuring techniques is that no single method is useable over a very wide range of altitudes. The rocket-exhaust method, however, can be used to give a continuous indication of wind velocity from the ground up to at least 85 km above the earth's surface.

In the experiment cited above (ref. 104), a cross-shaped array of nine microphones was set up on a flat area extending over a distance of about 1500 ft for each of the two axes. The electrical output of these microphones during the rocket ascension was recorded. The microphones were the hot-wire type developed by Texas Western College for the Rocket Grenade Experiment. These microphones were basically resonant at about 4.5 Hz. This very-low frequency range was considered best for long-distance sound transmission measurements, since the atmosphere would act as a low-pass filter and only the relatively low frequencies would be effectively transmitted over the distances involved in this experiment. Assuming that the vertical component of wind velocity would be negligible, that the source of sound could be considered a single point which maintains a specific flight path, and that the atmosphere would remain at a steady state during the measurements, the investigators attempted to determine the actual wind profiles by comparing the sound-arrival times. The cross-correlation of the microphone outputs was performed with a digital computer. Figure 17 shows a typical trace, indicating that the outputs of the three microphones had easily identifiable differences in wave form, and that good arrival-time measurements could be made. The

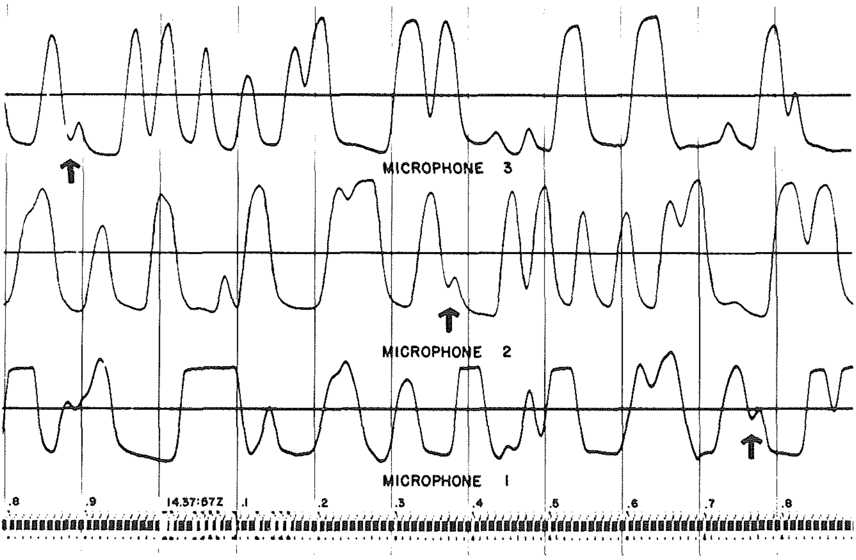


FIGURE 17.—Typical oscillogram of microphone outputs.

data were reduced and converted to wind velocity by a relatively complex method of calculation, which was essentially a form of ray tracing through the atmosphere (fig. 18). The figure shows the degree to which wind velocity obtained by this method correlates with conventional (Rawinsonde and Rocketsonde) measurements. Although much current meteorological work is performed

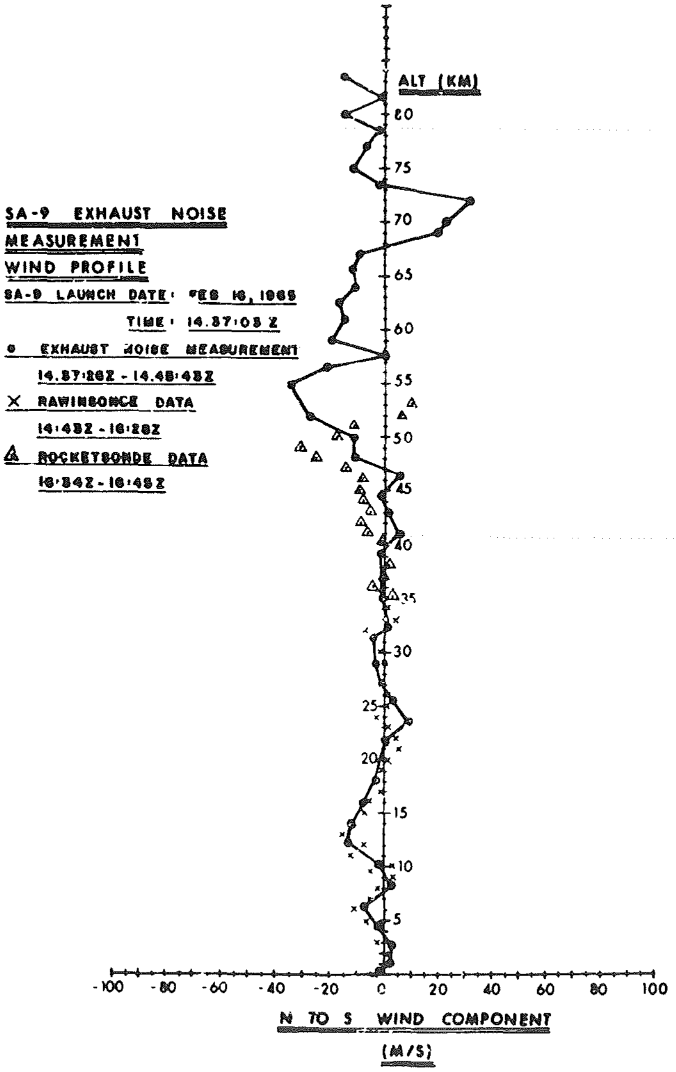


FIGURE 18.—Comparison of wind profile measured by the rocket-exhaust method and conventional (Rawinsonde and Rocketsonde) methods.

in support of aerospace activities, this technique for obtaining detailed wind information may prove useful in more basic studies concerned with the circulation and other characteristics of the atmosphere, which are of interest in nonaerospace applications. The most complex problem in determining acoustic propagation in the atmosphere is that of predicting whether or not noise generated by a large static booster test will cause disturbance at a long distance from the test site. It has proven very difficult, if not impossible, to predict actual focusing of sound at one spot on the ground, but determining the probability of any sound energy returning to the Earth's surface is generally sufficient to provide adequate guidance for test scheduling.

A report by Buell (ref. 105) contains a detailed discussion of predicting anomalies of sound transmission over long distances by using ray-tracing techniques to account for transmission through a layered atmosphere. In this report, the variability of accuracy in predicting such transmissions by the best methods of ray tracing based on short-term synoptic meteorological data is considered. It was found that this variability is approximately 5 dB, regardless of the magnitude of atmospheric variability normally occurring during a fraction of an hour or half a day. A significant factor is determining the probability of returning sound radiation at a given location; in other words, whether the ray-tracing method yields an estimate of sound intensity or none at all. It was also found that the effect of atmospheric variability on sound attenuation is different from that of the propagation pattern and may be determined by standard methods. The results of the analysis indicated that variability of atmospheric humidity is the most important factor.

The analytic methods of ray tracing and of dealing with errors that are presented in this report may be useful as references for individuals involved in the solution of problems related to sound propagation and its prediction. Most ray-tracing methods are difficult, if not impossible, to use, unless the concept of sharp changes in atmospheric conditions from layer to layer, which, in effect, produce corners in the rays, is understood. Since such cases are physically unacceptable for sound propagation estimates, such strategems as joining the straight-line segments of variations with parabolic arcs are proposed. The process of predicting atmospheric propagation is incredibly complex, but has been developed to such a degree of dependability that it is relied upon for scheduling or cancelling massive booster tests to ensure that populated areas remote from the test sites will not be disturbed.

A report by Heybey of the Aero-Astrodynamics Laboratory of

Marshall Space Flight Center deals with the prediction of acoustic-return probability (ref. 106). Only in simple cases is it possible to relate sound intensities of microwatts/cm^2, which have travelled over a long path, to the sound pressure level; that is, the objective level that will be measured by a microphone. It is indicated in this report that the calculation of the relationship between sound pressure level and intensity level has been formerly accomplished only for plane or purely spherical waves in a two-dimensional refraction case. For more complex patterns of wave travel (including three dimensional ones), the intensity level and the sound pressure level will correlate quite closely, usually within a fraction of a dB.

A series of lectures delivered at a NATO institute in 1966, in which the movements and turbulence of the atmosphere at altitudes of between 30 and 120 km are discussed, are contained in reference 107. The fact that acoustic propagation does not occur at extremely low frequencies in the atmosphere is emphasized in this document. Some of the acoustic analytic tools are recommended as useful for meteorological studies.

ACOUSTIC PROPAGATION IN LIQUIDS

Because acoustic pressure and flow perturbations are often important in the operation of various fluid systems, the Lewis Research Center has occasionally participated in a general experimental research program to determine the effect of acoustic disturbances in flowing liquid systems. Transfer functions for acoustic disturbances that are superimposed on the mean flow of liquid propellant in long lines of several geometric networks are reported in several NASA publications.

The first of these studies deals with determining the dynamic response of a long hydraulic line (ref. 108). The line tested was a stainless steel-tube 68 ft long, with a diameter of 1 in. and a wall thickness of $\frac{1}{16}$ in. The tube was rigidly supported at each end on bases set in concrete, and the central span was supported on stretched horizontal wires spaced at 2-ft intervals. As the fluid flowed down the pipe, the flow was modulated by passing through an orifice, the size of which was modified by an electrohydraulic servomotor. A multi-aperture orifice terminated the line. A strain gauge for measuring pressure and a hot-wire anemometer for measuring velocity were coupled to the fluid at each end of the line. For a portion of the test, a velocity transducer was also coupled to the downstream end of the line. The purpose of the test was to determine whether the conventional dynamic characteristics of such lines could be confirmed experimentally. The velocity of sound in the fluid was found to be in agreement with theoretically calculated values. Various terminating impedances in the form of orifices were placed at the downstream end of the line, and the driving frequency of the variable-orifice perturbation generator was swept through an appropriate range as the input and output velocities and pressures were measured. Having calculated the hydraulic characteristic impedance of the line and of the various terminating orifices, it was possible to predict line response and to compare it with measured values. The agreement was good except for the longitudinal vibration of the tube itself. The tube response was measured with the line empty and showed a resonance in the frequency of interest. The instrument used to derive response voltages from the transducers resolved the input into an amplitude value and a phase angle with respect to a reference signal, which, in this case, was the driving signal to the perturbation generator. With the output presented in this form, it was possible to subtract the response of the tube itself, as determined from the output of the external velocity transducer, from the hydraulic output readings, and thus, to compute the effect of tube variation. When this was done, the hydraulic transmission results showed almost perfect agreement with calculations. The tests showed that such low-viscosity jet fuels as JP–4, which was used in the experiment, had such small frictional losses that lossless transmission calculations were justified. It was also clearly established that pipe transmission and, hence, vibration must be considered in such calculations. Since all characteristic parameters were calculated directly from the inertial and elastic properties of the fluid and the tube, it was determined that these factors alone gave satisfactory prediction of dynamic response.

In 1962, a report by Blade, Lewis, and Goodykoontz described an extension of the hydraulic study discussed above (ref. 109). By placing a 90° bend in the center of the test section of the pipe, it was discovered that the massive fluid in a pipe having such an irregularity could impart energy to the pipe itself. The method of analysis used in the study made it possible to calculate the action of the entire system satisfactorily, including the motion imparted to the pipe by the perturbation of the fluid. The analysis involved these steps:

1. The mechanical forces on the moving pipe sections are expressed in terms of the pressure perturbations at the two ends and are related to the pipe-velocity perturbation by means of the mechanical impedance of the moving pipe, regarded as a viscous-damped spring-mass system.
2. The acoustic equations for undamped sound waves are used to relate the pressure and flow perturbations at the two ends of

each straight pipe section (fixed or moving). The flow perturbations are defined with respect to a fixed coordinate system, and the mean fluid-flow speed is neglected.

3. Equations based on continuity of pressure and flow including the flow equivalent of the pipe motion are used to relate conditions to adjoining pipe sections.
4. The relation between flow and pressure at one end of the line is defined by an expression for the impedance in terms of frequency.
5. The equations obtained in the preceding steps are solved to obtain expression for the desired transfer functions.

There was no evidence that the elbow, per se, caused a reflection or any disturbance whatever to the propagation of the fluid perturbations.

Another experiment in which fluid-dynamics perturbation was analyzed was reported by Blade and Lewis and Dorsch in 1963 (ref. 110). Substantially the same experimental setup was used. It was confirmed that the measured dynamic response was in good agreement with the anticipated value provided that the motion of the line itself was considered. The limitations of the analytic approach had become somewhat more specific than the general statements of the earlier studies indicated. Requirements included median-flow speeds of 20 fps, length-to-diameter ratios below 1000, frequencies below about 100 Hz, and fluids of low kinetic viscosity and high sonic speed, such as water, kerosene, alcohol, liquid metals, and subcooled liquified gases.

Fluids of higher viscosity under conditions of laminar flow were tested in the next study, which was reported in 1965 (ref. 111). The fuel used was an additive free SAE–20 motor oil. The original detectors were replaced with modern pressure transducers at the two ends of the line and were located at a point one quarter of the section length distant from the entrance orifice. A more modern servo-actuated valve was used to replace the variable orifice as a driver. The tube was terminated in a lossy orifice composed of a number of 0.04-in. holes in a plate. No reflection effects at the terminating orifice were observed by the investigators. A transfer-function analyzer was used to read the in-phase and quadrated components of the transducer outputs. Calculations of the attenuation along the line for various frequencies were accomplished by using classic damped-acoustic-wave procedures. Measurements were made to confirm these calculations, primarily presented as plots of attenuation of pressure perturbations versus frequency, and as ratio of phase constant to frequency (βf) versus frequency. The attenuation values were in good agreement with calculations and the β/f value remained essentially constant over the frequency range tested. The validity of the results was found to be limited to laminar flow of viscous Newtonian liquids within long firm walled, straight cylindrical, nonvibrating pipelines within the frequency range studied.

The next study in the series applied more practical communication techniques to suppress the perturbation under investigation. The report of this study by Blade and Holland appeared in 1966 (ref. 112). In the test, a shorter line of 66-ft length and JP–4 fluid were used. Thirty-three identical shunt assemblies were attached to the line at equally spaced intervals. Each assembly consisted of an element of inertance (a chamber containing some of the liquid) plus an element of compliance (a gas-filled flexible bladder immersed in the liquid) connected to the line through one of two kinds of resistive elements (either a group of 21 parallel Inconel tubes of 0.001-in. ID and 1.5-in. long or a commercial porous-metal bronze disc of $\frac{3}{16}$ in. diameter and $\frac{1}{2}$ in. thick). The line was terminated in an impedance approximately equal to the characteristic impedance of the line (this value varied with run conditions). The test results indicated that conventional calculations based on communication theory were a proper basis for predicting the attenuation measured, and that useful amounts of attenuation were achieved. One condition was established—that series perturbation-resistance elements must not be present.

PROPAGATION CHARACTERISTICS AS TOOLS

A different aspect of acoustic propagation in liquids is expressed in a rather long report presented by Clinch and Karplus in 1964 (ref. 113). This study was undertaken for the purpose of finding a means of measuring the relative amount of liquid and vapor in two-phase gas-vapor mixtures. It had been considered in the past that measurements of sound velocity or other acoustical phenomena in such a mixture could give information useful in determining the quality of the mixture. Consequently, propagation can be a potential tool rather than a subject of separate interest. Because two-phase fluids are used in many processes, many investigations of their flow have been undertaken in the past. To have a true understanding of the flow phenomena, it is of prime importance to acquire a knowledge of the relative masses of the phases (quality). In principle, the quality should be determinable by measuring some property of the fluid upon which quality depends. Under certain assumptions, the velocity of sound in a two-phase fluid is related directly to the quality. These assumptions require that thermodynamic equilibrium will exist between the phases during sound propagation. Under conditions of equilibrium, the velocity of sound as a function of quality may be calculated from the known thermodynamic properties of the constituent phases. The equilibrium condition is reached, however, only for very low frequencies.

In the analysis, it is established that there is a range of frequencies over which the sound velocity depends not only upon the quality, but also upon the phase distribution in a mixture as well as the frequency of the sound. Above this frequency range, the sound velocity becomes independent of the quality and assumes the value appropriate to the predominant phase. Thus, the ability to predict the quality from the measurement of the sound velocity is dependent upon some knowledge of the phase. In this investigation, an attempt was made to derive information about the significant parameters by considering the propagation of both continuous and shock pressure waves in a mixture of boiling liquid hydrogen and saturated vapor. The approach, however, is quite general and applicable to any two-phase fluid-vapor system.

The analysis was limited to a homogeneous mixture of vapor and liquid, the liquid being dispersed uniformly throughout the vapor phase in the form of very small droplets, like atmospheric fog. This model was chosen because there was some evidence that the fog-flow regime would predominate over a wide range of flow conditions, and because the underlying physical processes that occur between the phases during wave propagation could be more readily understood.

In summary, the analysis indicated that sound propagation in a two-phase fluid depends not only upon the relative masses of the phases, that is, the quality, but also upon the size and spatial distribution of the constituent phases. The propagation velocity will increase with sound frequency. At very low frequencies, the velocity depends only upon the quality, whereas at intermediate frequencies, the velocity is a complicated function of both the quality and aggregate phase sizes. At high frequencies, the velocity approaches a fixed value that is related directly to the properties of the predominant phase in a mixture.

In addition, calculations for the low-frequency velocity were found to agree with those reported by other workers. Experimental data for the high-frequency velocity in other two-phase fluids confirmed the view that the propagation velocity is determined by the dominant phase alone. On this assumption, the high-frequency velocity in the liquid hydrogen vapor mixture was calculated. Calculations at intermediate frequencies led to complicated expressions for the wave propagation constants. This was true even for an idealized two-phase fluid as, for example, a vapor fog containing uniformly spaced droplets of equal size. Simplified expressions taking into account drag and heat transfer between the phases yielded estimates of the relaxation times or time constants involved in these processes. These time constants determined the region of frequency and aggregate sizes of the individual phases in which these parameters have little effect on the propagation constant.

The sound velocity and absorption were calculated by using a simplified model, valid only for one particular value of the quality (critical quality). At the critical quality, neither evaporation nor condensation of liquid was observed for adiabatic pressure changes. At qualities greater than the critical value, the calculated time constant was primarily dependent on heat conduction and was further increased because of the additional heat transfer needed to evaporate the liquid. For qualities less than critical, increases in adiabatic pressure produced condensation which increased the effective heat transfer. The detailed computation accounting for the mass transfer ratio between the phases (in addition to simple heat conduction) involved estimates of the temperature gradients in the vicinity of the phase boundaries.

The precise meanings of the terms low, intermediate, and high frequencies used in the paper are relative, and their magnitude and range is determined by the droplet size and quality of the two-phase mixture. The following table has been constructed to illustrate the dependence of the frequency range on droplet size for a hydrogen mixture of critical quality at atmospheric pressure.

Droplet diameter	Low-frequency range	Intermediate-frequency range	High-frequency range
2μ	< 1.5 kHz	1.5 kHz to 36.5 MHz	> 36.5 MHz
20μ	< 15 Hz	15 Hz to 365 kHz	> 365 kHz
200μ	< 0.15 Hz	0.15 Hz to 3.65 kHz	> 3.65 kHz
2mm	< 0.0015 Hz	0.0015 Hz to 36.5 Hz	> 36.5 Hz

Application of the analysis given in this report to a direct measurement of quality in two-phase flow is limited to situations where the aggregates, i.e., droplets in fog or vapor bubbles in liquid, are extremely small. For normal droplet distributions, work in sound frequencies can most easily be accomplished in the intermediate range where the propagation velocity depends on the aggregate size as well as the quality. There are at present no known methods of separating the unknown variables, that is, the aggregate size and quality. With low-frequency sound waves in aggregates of droplets or bubbles of moderate size, it is difficult to measure very small phase differences in a progressive wave in the presence of turbulent noise in multiple reflected rays.

Calculations of the change of the shape of the pulses propagating through the liquid hydrogen mixture are illustrated in the report with examples. In the dispersion region, it was found that the changing of pulse shape is too rapid for making any precise measurements of the complex propagation velocity. In the presence of more complex two-phase-flow regions (for example, annular or plug flow), the sound propagation will be unpredictable both in space and time. Under these conditions, coupling between closely spaced sound transducers could possibly indicate whether the fluid between them is, at any particular instant, predominantly liquid or vapor. The relative duration of the passage of the vapor or liquid at any location could provide basic information on the phase distribution. The result is that, at high frequencies, the sound velocity is a function only of the simply connected phase, and not of diverse droplets or bubbles. This fact may be applied in two-phase flow research for measuring the flows of velocity of the dominant phase, which would facilitate determining the slip velocity between the phases if the velocity of the dispersed phase is independently known.

It may, therefore, be concluded that acoustic techniques have a specific, though limited, application for supplementing the more conventional experimental methods used in two-phase flow research. Useful data could be obtained by measuring the flow velocity of the dominant phase with an acoustic Doppler method. In more complex flow regions, it may be possible to resolve the spatial phase distribution by determining the difference in acoustic coupling when the fluid flows between sound transducers. The original idea of determining the quality of the two-phase fluids by measuring sound-propagation constants was found to be very difficult, except in the case of aggregates of extremely small flow.

ACOUSTIC PROPAGATION IN PLASMAS

Far removed from the conventional concept of acoustics as a study of sound frequencies is the study of acoustic waves in plasmas. These waves have properties that are mathematically related to those of conventional acoustic waves; a generally fixed velocity of propagation and many, if not all, of the properties of conventional sound have been identified. Investigations of these waves have been accomplished primarily in two fields: magnetohydrodynamics, specifically that of fusion reactions as sources of power, and the study of galactic gas and related ionospheric phenomena. This area of acoustics may be characterized as the acoustics of electrically conductive gases in externally and internally generated magnetic fields.

Investigations of acoustics in ionized gas by Kanwal are described in a set of lecture notes (ref. 114). The topics include the equations of magnetohydrodynamics, general properties, boundary-value problems, sound waves, and shock waves. The initial set of notes contains information regarding sound waves. The manner in which the study of magnetohydrodynamics has modified the theory of classical hydrodynamics is discussed, particularly the modifications of the conventional acoustic and acoustic-related wave phenomena in gases that have electrical conductivity and whose behavior is influenced by external and internal magnetic fields. The basic vector equations listed belong to the same class of symmetrical hyperbolic equations as the equations of electrically nonconductive-gas dynamics.

In fluids which are both compressible and magnetic, it is natural to expect that waves of condensation and velocity gradient will generally be neither transverse nor longitudinal and that their speeds of propagation will differ. Consequently, from purely kinematical considerations, not only spin but also stretching and shearing of fluid elements are carried by such waves. From the implications of the equations developed in the study, a main theorem is proposed.

The conclusions of the study are rather unusual in nature. Except under special circumstances, no wave carrying a condensation can propagate down the line of magnetic induction, but any other direction of propagation is possible. When the wavefront is not tangent to the lines of induction, there are four possible waves determined uniquely by the magnetic field, by the orientation of the surface which is intercepted, and by the conductivity of the fluid. One pair travels at supersonic speed, the other at subsonic, each wave-pair being made up of waves with different signs of velocity (i.e., travelling in opposite directions from the origin). The waves carry condensations (as in sound waves) and jumps in current density. They also differ within the pair in the sense of the current density. As the magnetic field approaches zero, the fast waves behave as ordinary waves of sound; that is, longitudinal waves carrying an arbitrary condensation in an arbitrary direction and propagating at the classical sound speed, while the slow waves become indeterminate material singularities. As the conductivity approaches zero, both kinds of waves become transverse waves like those discovered by Alfven, which propagate in incompressible inviscid fluids of negligible electrical resistance.

Further detailed analytic development of acoustics in magnetohydrodynamics is contained in a report by Schmid of Goddard Space Flight Center (ref. 115). This investigator formulated magneto-gas dynamics in a form using spinors, which is explained in an earlier report (ref. 116). In an extension of this analysis of dynamics, he obtained a spinor solution of sound wave problems by deriving a spinor formulation of the basic acoustic-wave equations. The solution is completely relativistic, and satisfies Euler's continuity equation and the adiabatic condition for sound waves of macroscopic wavelength. For wavelengths of the order of atomic dimensions, independent terms that are completely negligible in macroscopic waves become important and drastically alter the form of the solution. Thus, the spinor solution of the sound-wave problem automatically breaks down at the point where classical mechanics breaks down, namely, when the characteristic length of the problem approaches atomic dimensions.

The spinor formulation of fluid dynamics is applied to the one-dimensional problem of the sound wave in an electrically neutral perfect gas. The solution is achieved by means of a perturbation on a simple zero-order solution, which corresponds to a fluid of constant density moving in the positive z direction with constant velocity. By choosing the particle spins (which are insignificant in any macroscopic problem) to be aligned in the z direction, it is possible to reduce two of the four spinor components to zero, thereby reducing the complexity of calculation. The fluid enthalpy, which is regarded as the driving function of the problem, is next assigned a sinusoidal, time-independent variation in the z direction, and the spinor equations are solved to find the spinor functions consistent with this form of variation in the enthalpy. The solution is accomplished using the first order perturbation of approximation in which the perturbation parameter is the ratio of the maximum change in the specific enthalpy to the particle rest-mass. For practical problems, this ratio is always very small.

Once the spinor equation has been solved for sinusoidal variation in enthalpy, spinor relations are applied to calculate the fluid-flux density, which is constant, and the particle density, which has a sinusoidal variation of the same wavelength as the assigned variation in the enthalpy. The conservation of the particle energy, which is a condition required by Euler's equation, is maintained. Euler's equation is reduced to a form in the report that states that the sum of the kinetic and thermal energies per particle must remain constant.

The spinor equations, like Euler's equation, must be supplemented by the adiabatic condition relating changes in the density and enthalpy, respectively. The wave appears to be stationary because the fluid flowing in the +z direction with exactly the same speed as that with which the wave is propagating in the −z direction. The adiabatic condition yields a description of the fluid velocity, which is the conventional expression for the speed of sound in terms of the absolute temperature of the gas.

Finally, it is shown that, although the effects of particle spin are completely negligible for macroscopic wavelengths, they become important when the wavelengths are of atomic dimensions; consequently the classic solution is no longer valid.

A study of acoustical phenomena in the ionosphere is reported by Calvert of the University of Denver (ref. 117). An edited version of the introduction gives the main purpose and accomplishments of this investigation.

The propagation of pressure disturbances in an ionized medium is of considerable geophysical interest. At altitudes of between 50 and 100 km, corresponding to the ionospheric D layer, the daytime atmosphere is a very weak plasma with an ionized fraction that may approach 10^{-10} at the upper boundary. The pressure range in this region is from about 1 mm down to 10^{-4} mm Hg, though the mean free path increases from 10^{-3} to 20 cm. This region corresponds to the upper altitude limits for ordinary acoustic propagation. Between 100 and 150 km, which is the lower E region of the ionosphere, the ionized fraction rises to about 10^{-5}, and the mean free path increases to about 45 m. Only low-frequency acoustic waves can propagate under these conditions without almost completely being absorbed. At still greater altitudes, the ionized fraction continues to increase as collisions between the molecules become less frequent. With respect to pressure disturbance to propagation, therefore, the atmosphere represents a continuous gradation of conditions from those in which molecular collisions are dominant and ordinary acoustic propagation predominates, to those in which collision and ion-wave propagation are important.

Another application of acoustic analytical methods to obscure gas dynamic phenomena is reported in reference 118. An abstract of this report is quoted:

> The elementary formula for the pressure and the speed of sound in a statistically isotropic homogeneous cosmic-ray gas are worked out. Cosmic-ray observation near earth give a cosmic-ray energy density of 1.29×10^{-12} ergs/cm^3, a pressure of 0.45×10^{-12} dynes/cm^2, and a compressibility equal to 0.66×10^{-12} ergs/cm^3. There is reason to believe that the interstellar values are not significantly higher than near earth.

CHAPTER 4

Effects of Noise

The deleterious effects of noise on both people and inanimate objects cover a wide range, and many important effects are referred to indirectly in other parts of this survey. The discussion in this chapter will deal primarily with the effects of noise on humans, near and distant objects, and structures. Here, too, the process by which noise penetrates complex structures to produce its effects will be considered.

RESPONSE OF HUMANS TO NOISE

A variety of sounds, particularly intense ones, can affect humans in many ways, by causing actual physical damage to tissue, impairing performance directly, and causing annoyance that may indirectly impair performance. A study was prepared by the School of Medicine of Tulane University (ref. 119) in which certain aspects of physical damage to humans were examined. As part of this study, a test was conducted in which the possibility of actual physical damage to humans was determined indirectly by exposing 11 cats and 2 monkeys to sound pressure levels as high as 154 dB, with variable effects. At least one monkey was observed to have visible brain damage; and significant changes were noted in the EEG potentials evoked in the brains of these animals by exposure to both light and sound before and after the severe noise exposure. Also in this study, when the EEG measurements of humans were made before and during intense (but not damaging) exposure to rocket noise, various paroxysmal abnormalities in some test subjects were observed. Hearing threshold tests were made on 97 male subjects exposed to various noise levels demonstrating that moderate exposure does not significantly affect thresholds for pure tones. It was noted, however, that some individuals were significantly affected by such sound exposure. As an overall check, some 25 persons with previous histories of exposure to static firings were examined for evidence of vestibular damage but none was noted. This research indicated that it is extremely difficult to evaluate the potential hearing or tissue damage caused by intense noise, but any exposed person must assume that the possibility of damage exists.

The presence of large amounts of very low-frequency noise as well as the sonic-boom shock waves from large rocket boosters made it desirable to test human response to low-frequency sound. Since no previously constructed testing facilities were usable at elevated sound pressure levels in this frequency range, the Langley Low-Frequency Noise Facility was designed to study low-frequency noise effects, including sonic-boom effects on houses and commercial buildings, and the effects of low-frequency noise on humans. This facility is described in reference 120; so, too, is its use in testing human response.

As part of the study, five individuals (with a background in both medicine and engineering) were tested in a series of short-duration exposures to narrow bands of random noise over a range of sound pressure levels. In these tests the following factors were monitored: (1) vision (checked by the Snellen E vision test), (2) motor function (checked by circle tracings), (3) spatial orientation (checked by the past-pointing target), (4) cardiac rhythm (checked by pulse rate—EKG), (5) speech intelligibility (checked by having the subject speak a prepared list of "rhyme" words into a noise-cancelling microphone), (6) individual subject response (checked by acceleration), and (7) reaction times and overall tolerances (checked by the subject's opinion). The general results obtained during these noise-explosion tests are shown in figure 19. Subjects were exposed to noises 40 dB greater than in any previous tests at frequencies as low as 1 to 2 Hz, and to noises 35 dB greater at frequencies up to 50 Hz. Exposure levels closely approached those at which ear pain is known to occur, and the results indicated that a man can withstand exposures at these low-frequency noise levels without physical damage. However, the subjects experienced

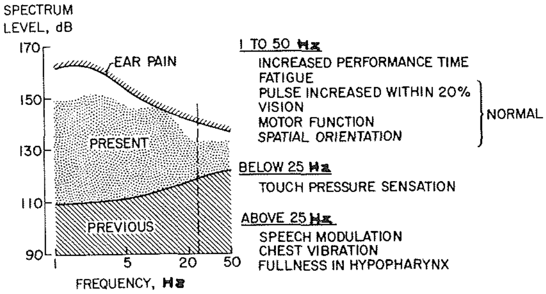


FIGURE 19.—Summary of noise exposure levels and general results obtained for noise exposure tests in Langley Low-Frequency Noise Facility.

some annoyance, discomfort, and fatigue; they also performed tasks at slower rates.

The entire field of noise and loudness is reviewed in subjective terms in reference 121. In this report, Kryter first considers the specification of loudness. Knowledge about this aspect of sound has reached a stage where two procedures for calculating the loudness of a complex sound from purely physical measurements of octave, half-octave, or third-octave band spectra have been proposed for standardization on an international basis. The methods are those proposed by Stevens and Zwicker.

As a result of knowledge gained, it has been widely proposed that the perceived noisiness, or "unwantedness" of a sound, is more important to the evaluation of man's noise environment than its loudness. The following physical and temporal aspects of a sound, listed in order of importance, have been found to influence, in general, man's rating of subjective noisiness: (1) intensity level, (2) spectrum shape and bandwidth, (3) spectral complexity (presence of one or more pure tones in a band of random noise), and (4) duration.

Although much remains to be done, various methods have been developed to calculate perceived noisiness of a complex sound from either third-octave or full-octave band spectra. Using procedures that weight the spectral regions differently from those used for calculating loudness, national and international standards have been proposed in which perceived noise levels (PNdB) derived from these procedures are used to evaluate aircraft noises. Recently, additional procedures have been proposed to modify the original calculations of PNdB levels, taking into account the effects of pure tones and duration upon the perceived noisiness of complex sounds.

In addition, Kryter points out that the original assumption that the degree of loudness-determined acceptability led to considerable effort to define loudness. This involved knowing something about the relative loudness of tones at different frequencies, the influence of the spectrum bandwidth on loudness, and the actual relationship between an increase in objective sound pressure level, as well as an increase in loudness as a subjective phenomenon. Fletcher, Steinberg, and Munson (refs. 122 to 124) made the first major attempts to define and measure loudness. Stevens later (ref. 125) suggested that the unit of loudness be called the "sone," and that a loudness of one sone be assigned to a 1000 Hz-tone set at a sound pressure level of 40 dB. (The reference of this level is the standard 0.0002 microbar.) Fletcher and Munson (ref. 124) prepared the first curves of equal loudness contours and others have since refined them (ref. 126). Kryter's report (ref. 121) has an extensive list of references on this subject.

The Stevens method for calculating loudness uses the general principle of establishing the sone value of the loudest band (usually an octave band) of a complex sound and then adding a fractional part of the sone values of the remainder of the bands. These fractions for full octave bands were 0.3, for half-octave bands, 0.2, and for the third-octave bands, 0.15. This method was later modified to a form known as Mark VI, which has been adopted by the American Standards Association as the procedure for calculating the loudness of noise measured in either octave, half-octave, or third-octave bands. In this method the loudness of a sound is expressed in terms of the sound pressure level in dB of the reference sound rather than in units of loudness or sones. The result is called the loudness level expressed in units of phons; this unit of measurement replaces the mathematically equivalent decibel, and indicates a ratio derived from psychological units (sones) and not directly from physical measurements of sound pressure. Furthermore, the phon is obviously not defined from the ratio of two loudness levels, as a decibel is defined from the ratio of two sound-pressure levels.

The International Organization for Standardization has recommended the Mark VI method for calculating the loudness of sound measured with octave band filters; and Zwicker's method of calculation when the sounds are measured with third-octave band filters (ref. 127). The Zwicker method, a critical-band concept, is based on the capacity of a noise band of a given width to perform a masking function within the ear. The bandwidth of a critical band of noise centered on a particular frequency is that bandwidth which produces as much masking as any increased width in the band. In other words, if one increases the bandwidth from essentially zero to the critical-band value, the masking capacity becomes greater until it reaches the critical value. At that point, widening the band has no further effect. The physiological and psychological implications of this are quite direct, but too complex to consider here. In this method, Zwicker assumed that there is a partial correspondence between masking and loudness as substantiated by data on the critical bandwidth of the ear. He developed a means for graphically calculating loudness under both diffuse and free-field conditions. He also designed a special graph, similar to that shown in reference 127, on which the sound spectrum was plotted. On the graph, the horizontal lines indicate the spread of masking, and that proportion of available nerve impulse units in the ear made operative by exposure to a given sound.

Wherever the plotted curve crosses one of these horizontal lines, a line is drawn and then all the lines are joined. The area under this series of joined short lines on the graph is proportional to the total loudness. A planimeter may be used to measure the areas on the graph encompassed by the plot of a given sound; these areas can also be estimated with reasonable accuracy by visual inspection.

Zwicker has defined a sone as the area encompassed on the graph by a third-octave band of noise centered at 1000 Hz, and a sound-pressure level of 40 dB. This includes the additional area encompassed by the dashed curve accounting for the upward spread of loudness (masking). Numerically, the Zwicker method differs about 3 to 6 phons from the Stevens method and is directly consistent with experimental data. Its application, however, is quite complex. Other proposed methods, particularly Munson's (ref. 128), are less complex but are based more on observation than experiment.

So far, the methods discussed in this chapter have been concerned with the loudness of pure tones or narrow bands of noise relative to a reference sound. Another important aspect of loudness involves the growth of loudness with intensity; that is, the establishment of loudness vs intensity scales. The evaluation of these scales is very complicated, requiring analysis of different loudness scales for monaural vs binaural listening; the assignment of numbers to the subjective magnitude of loudness; and the adjustment of a sound level until it has a given ratio of loudness to another sound for making loudness-ranking scales. Also the equisection or equal-interval loudness scale in which two sounds are presented at different levels, making it necessary to adjust the level of another sound to lie equidistant in loudness between the other two, further complicates evaluations. Kryter (ref. 121) analyzed this aspect of loudness and concluded that, if the general interest in loudness judgement in real life situations is more in terms of apparent magnitude or relative loudnesses than in the terms of equal loudness intervals, then it would appear that the equal loudness scale based on the magnitude estimation is more applicable for general use.

Most testing of loudness judgement has been done with sounds of short duration. In these tests loudness presumably remained constant after the first 100 to 200 millisec of duration. There were, however, some exceptions such as the apparent growth or "flutter" in the loudness of noise bursts repeated over 20 to 320 sec. Also, it was found that a pure tone and narrow band having a level of 90 dB increased 2 to 3 dB in loudness during a 10-min exposure.

However, there was a decrease of about 5 dB in the loudness of the same combination of tone and noise presented at 70 dB for 10 min. This subject is particularly complex and no satisfactory explanation or method of using time in the evaluation of loudness has been suggested.

In addition, a sound-level meter with a weighting network can be used to measure loudness. Methods in which this meter is used include: (1) the so-called *C* scale, which is based on the Fletcher-Munson equal-loudness contours for the sound level of 100 phons, (2) the *B* scale for the same curve for the 70-phon contour, and (3) the *A* scale for the 40-phon contour. These rather simple methods have been widely employed to measure loudness, but they do not give really useful results.

The most important aspect of the measurement of noisiness and loudness appears to be the recent realization of the difference between the loudness and the annoyance value of a sound. In 1958, a series of tests were conducted in which subjects individually adjusted the sound pressure level of a recorded fly-over sound made by one type of jet aircraft until it became as acceptable or "noisy" as sounds from other types of jet or propellor-driven aircraft. These tests were designed to develop an objective measure of the noisiness value in an everyday situation. They demonstrated that readings on *A*, *B*, and particularly *C* scales, and the loudness level in phons as calculated by the Stevens method, did not predict the noisiness of the sound as well as desired. Some earlier experiments, performed in 1943 at the Harvard Psychoacoustics Laboratory (ref. 129) to investigate the annoyance value of sound, were used by Kryter (ref. 130), despite meager data, to predict the results of the aforementioned tests with aircraft noise. As a result, Stevens' equal loudness contours for octave bands of noise were modified to account for the additional contribution made by the higher frequencies to the subjective acceptability or noisiness of complex sound. The remainder of the Stevens method for calculating noise loudness was used to calculate the relative "noisiness" of complex sound. To distinguish the modified loudness contours from the regular loudness contours as well as to clarify loudness terminology, the "noy" was designated as the unit of noisiness. One noy was defined as the noisiness of an octave band of noise centered at 1000 Hz with a band-sound-pressure level of 40 dB. PNdB was created as the analog of the phon.

The perceived noise level in PNdB of a given sound is the sound-pressure level of an octave band of noise at 1000 Hz, which is considered as noisy or unacceptable as the given sound. Determination of the perceived noisiness of a sound can be accomplished by using available figures and tables (ref. 131) and the following formulas for a total effective noy value (N):

1. For octave-band spectra $N = n_{\max} + 0.3\ (\Sigma n - n_{\max})$
2. For third-octave band spectra $N = n_{\max} + 0.15\ (\Sigma n - n_{\max})$
3. For ten-octave band spectra $N = n_{\max} + 0.07\ (\Sigma n - n_{\max})$

where $n_{\max}$ is the number of noys in the noisiest band and Σn is the sum of noy values in all the bands. These formulas and the band factors represent, respectively, the functional relationships found by Stevens between loudness and the bandwidth of noise. The perceived noise level of sounds not involving intense pure-tone components or other sharp spectral variations may be estimated to some degree with a simple sound-level meter with a weighting network shaped like the 40-noy-equal-noisiness contour (ref. 132). A sound-level meter with this weighting network, called "N" weighting, is used at several airports in the United States for monitoring the noise level of operating aircraft to determine if and when such levels exceed certain limits. These readings can be expressed as dB (N), analogous to dB (A), or dB (C) (refs. 130, 133).

The effect on perceived noise of intense pure tone in complex sounds has been calculated by some complex analyses. Kryter and Pearsons (ref. 134) devised a correction factor that could be added to the sound-pressure level of the various bandwidths of noise to compensate for the presence of intense pure-tone sounds. This factor is shown in figure 20. A general set of pure-tone

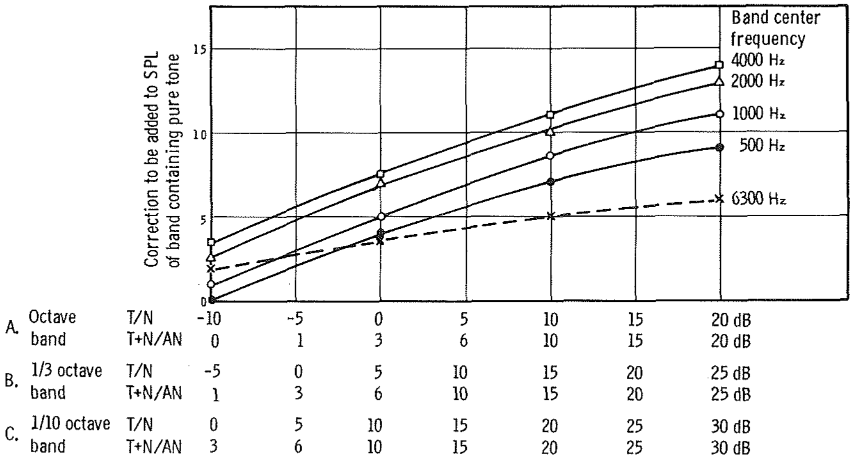
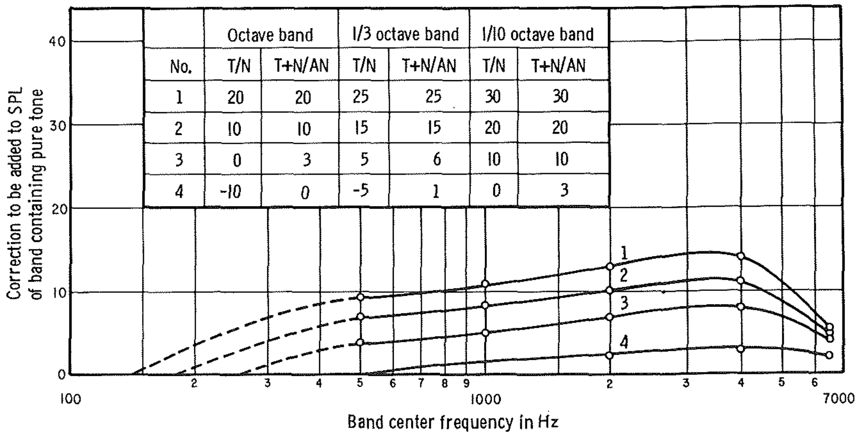


FIGURE 20.—Adjustment to be added to sound-pressure level of band containing pure-tone component prior to calculation of perceived noise level.

adjustments as a function of frequency is shown in figure 21. Multiple and modulated pure tones were further investigated by Pearsons, Woods, and Kryter (ref. 135) who found that: (1) the amplitude and frequency modulation imposed upon one or more pure tones did not increase the subjective noisiness of these sounds relative to the noisiness of the steady-state or unmodulated sounds, and (2) the presence of either modulated or unmodulated pure tones imposed on a broadband background noise did not increase the noisiness of these complex sounds relative to the noisiness of the broadband sound without pure tones. These findings indicated that the additional noisiness effect of the pure tones disappeared in the very complex mixtures of pure tones. Theoretical analysis of this occurrence was not entirely conclusive, however.

Kryter and Pearson (ref. 134) finally recommended that the calculation of perceived noise level be made by using "the 3 dB rule," which implies that if a band exceeds its adjacent band level by 3 dB, a pure tone is present. Therefore, adjustment of curves in figures 20 and 21 could be made, whenever this occurs. In general, the various methods of measuring perceived noisiness can be ranked in this order of merit: (1) dB (C), (2) db (A), (3) phons-Stevens (S), (4) phons-Zwicker (Z), and (5) PNdB.

An example of the criteria for PNbB noisiness, established by Kryter and Pearsons, is given in reference 136. In this study the effects of spectral content and duration on perceived-noise level are discussed, and the results are integrated with the data on



	Octave band		1/3 octave band		1/10 octave band	
No.	T/N	T+N/AN	T/N	T+N/AN	T/N	T+N/AN
1	20	20	25	25	30	30
2	10	10	15	15	20	20
3	0	3	5	6	10	10
4	-10	0	-5	1	0	3

FIGURE 21.—General adjustments to be added to sound-pressure level of band containing pure-tone component prior to calculation of perceived noise level as a function of frequency.

the loudness and noisiness of complex sounds described in reference 121. As part of this work, a number of experiments were conducted in which listeners equated a wide variety of sounds with respect to noisiness (equal acceptability) and loudness. The principal findings drawn from this study include:

1. On the basis of the data obtained from approximately 250 subjects, new equal-noisiness contours and tables for calculating perceived-noise levels were determined.
2. Over a range of durations from 1.5 to 12.0 sec, sounds were judged equally acceptable by subjects when the sound pressure level was reduced by 4.5 dB for each doubling of the duration. Variations in rise and decay times from 0.5 to 4.0 sec did not significantly influence their judgments.
3. A combination of pure tone of sufficient intensity with a band of filtered white noise was judged noisier than the same band of noise at the same overall sound-pressure level as the tone-plus-noise. However, the loudness of the band of noise at a constant overall level was not appreciably affected by the addition of the tone.
4. Calculated measurements of perceived noise level, loudness, and the readings on *A*, *B*, *C*, and flat scales on a sound-level meter were determined for a variety of real and artificial sounds of equal duration when these sounds were judged to be equally noisy or acceptable. Considering both absolute values and variability in the results, the various means for predicting the judgement data were ranked as follows: (1) PNdB, (2) phons-Zwicker, (3) phons-Stevens, (4) flat, and (5) *C*, *B*, and *A* scale of the sound-level meter.

EFFECTS OF NOISE ON STRUCTURES

The discussion of the effects of noise on structures in this survey is limited to the structures found in aircraft or spacecraft. The structural effects are divided for convenience into the powers of sound energy being coupled into the structure, the manner in which the energy traverses the structure, the way energy transmission can be reduced (noise reduction), and the manner in which the energy can damage the structure (primarily by fatigue).

Boundary-Layer Noise and Coupling to Structures

Considering the powers of noise coupling generated by turbulent air flow into a structure, the noise is usually created at a covering panel and is coupled into the panel as vibration entering the structure. Some measurements of noise transmission and stress response of a thin Duralumin panel in the presence of air flow are reported by Kantarges (ref. 137). As part of this work, several cases were studied, the primary differences being that either a reverberant or an absorptive sound chamber was attached to the back of the panel, and the air flow past the panel was either directly impinged on the panel producing aerodynamic coupling or passed some distance above the panel so that the total energy coupling was only acoustic. When an absorptive chamber was attached on the back of the panel, the inside noise spectra appeared to have peaks of energy at frequencies corresponding to normal modes of the panel. However, when a reverberant chamber was attached back of the panel, the response was considerably smoother and no evidence of the panel modes was apparent. In the method of sound excitation by which the air flow is not directly impinged on the panel, the noise between the outside and the inside of the panel was reduced roughly in accordance with the weight law for sound transmission. In the "flow attached" method (i.e., with the sound impinging on the panel), however, the weight law did not apply. This may have resulted from the excitation of much higher modes of the panel in direct contact with the air.

In reference 138, Smith presents an analysis of the amount of energy coupled between a sound field and a simply-supported rectangular panel which is extended to other forms of panel support. Whether or not the sound was generated turbulently at the panel was not considered. Maidanik (ref. 139) concluded that the coupling between sound waves in a fluid and the bending vibration of a simply-supported rectangular panel, surrounded by an infinite rigid baffle, was proportional to the length of the panel's perimeter when the frequency was less than the critical frequency (the frequency at which the wavelength of three straight-crested banding waves in an infinite panel of the same thickness, equals the wavelength of three space waves in the unobstructed fluid). Factors of proportionality in the Maidanik relation did not involve any parameter of the panel except the ratio of frequency to the critical frequency. Depending on the nature of the mode, the simple conclusion was drawn that the coupling of sound to structures with clamped edges is twice that for simply supported edges, even in the fundamental mode. However, this spatial mean-square deflection must be equal in both cases being compared, and the analytical expression of coupling as a function of critical wave number will differ for identical structures vibrating in the same mode with different boundary conditions. According to this report, the fundamental mode vibration of a nearly square panel is yet to be investigated.

In 1964, Midwest Research Institute developed a computer program to calculate the flutter of flat panels in supersonic air streams (ref. 140). The computer program was tested with a few numerical results but no specific experimental confirmation had been carried out at the time the study was published. Although the program was written for the IBM 7094 computer, the age of this computer limits its usefulness, even though the program is undoubtedly adaptable. In reference 140, the author further indicates that the technique in a single computer run obtains further points for up to 6×6 flutter determinants. A single test of numerical results with a flat panel having free side edges, front edge clamped, and rear edge effectively pinned, showed that the program can predict the onset of first-mode flutter in good agreement with the experiments or a Mach number less than 1.2. For a Mach up to 1.3 there is also good agreement between theory and experiment on the onset of first-mode flutter, but the theory indicates that thicker panels will flutter in the second mode, a fact not confirmed by experiment.

Transmission of Sound Through Structures

The difficulty in making analytical predictions of acoustic transmission through structures is mentioned by Rollin in reference 141. In this study, hemispherical and conical fiber-glass nose cones were investigated to determine whether external noise could propagate sufficient energy to damage electronic equipment inside a nose cone. As a result of these investigations, it was found that in a hemispherical nose cone sound attenuation was reduced at lower middle frequencies when it was close to the noise source. Also, it was noted that intensity had little effect on transmission loss except for high frequencies, and that spectral distribution and standing waves within the cone were scarcely a function of geometric position. The conical nose cone showed some sensitivity of spectral distribution to geometric location but less sensitivity with increasing distance from the apex. In addition, specific evidence of internal standing waves in the forward part of the nose cone was observed.

A further analysis of the transmission of sound through structures is presented in reference 142. In the work it describes, a means was sought to determine analytically the mechanical transmission of a particular structure, primarily by designing an accurate theoretical model. Although neither spacecraft sound transmission nor shroud-enclosed structures may be of much interest to the nonaerospace community, the analytical methods described in the reference may be useful. In this report a specific example is given of the vibration-transmission-analysis procedure known as statistical energy analysis. The analysis indicated a major acoustic transmission of vibratory energy to the interior through the air-filled voids of the structure rather than through the mechanical trussing frame that holds the assembly together. This rather unexpected finding seems to be typical of such structures.

Another report (ref. 143) gives a comprehensive view of structural transmission of vibration and sound. The summary states:

> This report is designed to be a systematic development of some new techniques for analyzing structural vibrations and the interactions between sound fields and structural vibrations. In its application to structural vibration, the approach is quite new, having been motivated by the lengthening roster of difficult questions concerning vibrations in very complicated structures—buildings, missiles, ocean vessels, etc.—which are caused by a complicated set of forces. The new techniques rely upon an old trick: to make a "difficult" problem "easy," ask the easy questions. It is astounding how often the answers to easy questions will suffice.
>
> In the classical approach to a vibration problem, one usually asks, "What is the dynamic displacement of a particular point at a particular instant?" Now, in many practical problems, this is a most unreasonable question. . . . Even if an answer were forthcoming, from the ideal computer that analysts dream of, it would not be useful because particular points and particular instants are not really of concern, and a collection of data for all points and all instants would be overwhelming.
>
> To get a useful answer, some different question must be posed; let us try, "What is the average dynamic response (in a root-mean-square sense) when that average is performed both in space and in time?" This is better; at least the answer is one handy number. However, too much information has been lost in the process. For example, the answer says nothing about the time rate of change of response (i.e., about the frequencies involved), and such information is often important.
>
> The nature of the problem and some idea of the answers desired can be brought out by describing a typical practical situation. A very large rocket carries a moderately large capsule inside of which is mounted, in various ways and positions, some packages of delicate electronic instruments. Too much vibration of any one of many vacuum tubes, for example, will cause the whole rocket to misbehave. It is thought that the vibration may be caused by sound from the rocket engine passing through the capsule, reverberating about inside, and forcing the package of electronics. An estimate of the vibration generated in this manner is desired so that possible protective modifications to the structure and the instruments can be evaluated in a rational manner.
>
> The sound inside the capsule is found to be an extremely complicated function of time. It is a more or less random noise, although the energy is not distributed uniformly in frequency. Moreover, because of the limited space in the capsule, sound does not reach the package from any single direction. The sound bounces around in the space, and is repeatedly directed from many different angles, a fate which markedly affects the spatial distribution of force on the package.
>
> The vibratory response of the package to sound waves can be studied in the

laboratory, irradiating it with a pure-tone wave incident from a single direction. One will then typically find that the response at a single point fluctuates tremendously as frequency is varied, being very large in small regions of frequency near the natural mechanical resonances of the package. Figure 22 is an example of the records that are obtained in tests of this sort. At any one of these natural frequencies, the response may vary quite considerably, depending upon the angle from which the sound wave arrives. Finally, the magnitude of response varies from point to point, when frequency and angle of incidence are held fixed.

Upon inquiry, one discovers that the various electronic elements are sensitive to vibration in various ranges of frequency, and that their exact locations either are not known, are subject to change, or are distributed widely throughout the package. It is now evident that no exact question can be posed; it is needless to search for exact answers, of the type we called "classical". Only some sort of average, statistical estimates of response are required.

In this report we shall develop analytical procedures for obtaining estimates of this sort. In crude outline, the procedures more or less parallel the experimental laboratory study just described. From design drawings, one estimates the average number of resonances expected in a moderately broad band of frequency and the spatial distribution of response amplitude for a "typical" mode of resonance. With this information, one estimates the average response of a single "typical" mode to sound waves of noise incident from many various angles. The product of this average response per resonant mode by the average number of modes in a frequency band yields an estimate for the space-time average response in that frequency band. The process is repeated for different bands.

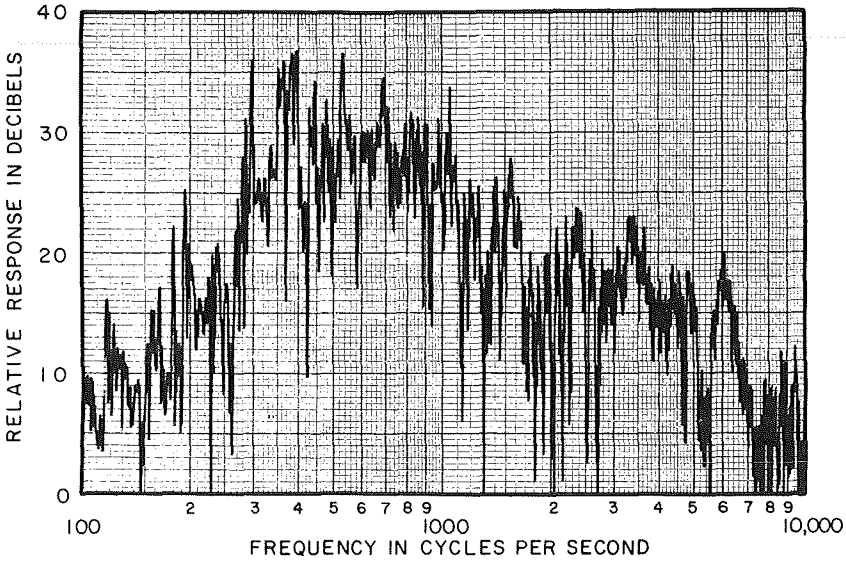


FIGURE 22.—Vibratory acceleration at one point of an aluminum panel exposed to a pure-tone sound wave of constant pressure and slowly varied frequency (20 db corresponds to a factor of 10 in response).

It is, of course, hopeless to attempt to find the exact characteristics of individual modes in the early phases of such an analysis. The saving feature of this new approach is that many of the average characteristics—number of modes in a frequency band, average coupling to sound incident from various angles, etc.—are insensitive to those details of construction which render impossible the exact analysis.

The aims of the present study are three-fold: (i) To outline a conceptual framework for analyzing the vibrations of complex distributed systems and the interactions of several systems. The approach proceeds by (a) a multimodal description of the vibrations of a system; (b) characterization of the modal response by the vibratory energy involved, and of the interactions by energy flux; (c) formulation of statistical average estimates of the dynamic parameters of various systems. (ii) To incorporate the principal results of earlier studies of vibratory interactions between sound fields and bending vibration fields in panel-like structures. (iii) To establish a unified basis for continuing research and extensions to new problems.

It is anticipated that many readers of this report will be non-specialists in one or another of the pertinent technical fields: acoustics, mechanical vibrations, and statistics. For this reason, the report develops the necessary concepts of each field from principles so fundamental as to bore the specialist. However, some familiarity with calculus and vectors is presumed.

The simple resonator, consisting of a mass, a spring, and a dissipative mechanism, is the analog for response in a single natural mode of a complicated structure. Chapter II is a study of the response of a single resonator and of sets of resonators. These mechanically simple problems furnish a ready opportunity to introduce many of the fundamental concepts: spectral analysis, mechanical impedance and its relation to energy, frequency-dependent coupling parameters, modal density, ensemble averages, etc.

Sound waves are discussed in Chapter III. From basic principles, the treatment proceeds to those concepts later required for analyzing the coupling between sound and structures: acoustical energetics, sound generation and radiation impedances, wave number vector and trace wave number, room acoustics, modal density, reverberation, and diffuse fields.

Structural vibrations and waves are presented in Chapter IV. Only bending (flexural) motion is considered, since practical response problems in extended structures are associated almost exclusively with bending. The treatment closely parallels that of sound waves in the previous chapter. An example of coupled mechanical systems is discussed.

Sound waves and structural vibrations are finally brought together in Chapter V. Here, the method for modelling structural vibration by the oscillations of a set of simple resonators is considered in detail. The concepts of directivity and reciprocity are introduced. From results in Chapter II, formulas are derived for the one-mode and multi-modal response of a general structure to noise and diffuse sound fields.

Chapter VI considers the evaluation of coupling between sound waves and bending vibrations of flat beams and panels. Formulas appropriate to numerical prediction are given. Comparisons between experiments and the theory are shown.

As a general technique, the procedures outlined in this report are in mid-evolution. First results are but a few years old; refinements and extensions are matter of current research. Chapter VII contains a survey of the literature and current research, for the guidance of interested readers.

This report (ref. 143) does just what the above summary says it does and it should remain a useful document for some time to come.

Lyon and Maidanik prepared a brief review of the earlier work on the method of statistical vibration analysis of structures (ref. 144). Another report (ref. 145) gives a specific example of the statistical system of sound analysis and vibration transmission noted above. In this report, the noise reduction provided by a rectangular box that is calculated either by classical methods or by the method of energy averages is considered. The simplicity of the system allows comparison of the two methods. The transmission behavior of the box depends on the relationship of the frequency tested to the lowest mechanical and acoustic resonance frequencies and the critical frequency of the walls. Noise reduction is the same for both external and internal sound sources if they are diffuse, but noise reduction of the rectangular shape at low frequencies is much lower than that of an equivalent spherical shell. At high frequencies, the lowest mechanical-resonance control of the noise reduction may become negative. At still higher frequencies, the modal response becomes so complex that it is not identifiable as such, and the noise reduction rises smoothly. At the critical frequency the noise reduction falls to a value short of that predicted. This system is particularly valuable for its operational simplicity.

Reduction of Noise in Structures

In reference 146, low-frequency noise problems for a limited class of structures including multiple-shell spacecraft were analyzed. The model-design and analysis in the report are applicable to a much wider field, however, and the findings can be best presented by quoting its introduction, summary, and general comments:

> There is an increasing interest on the part of engineers in the low-frequency sound transmission of aerospace structures. The prime reason for this interest is the discovery that low-frequency noise may have physiological and psychoacoustic effects on man (refs. 147 and 148), coupled with the fact that large space vehicles are exposed to high levels of low-frequency acoustic excitation from large rockets and from aerodynamic excitation (ref. 149). Quite aside from spacecraft applications, low-frequency noise reduction considerations are important also in the design of enclosures for the acoustic isolation of small and compact electromechanical and electronic assemblies.
>
> The sound-isolation effectiveness of an enclosure for a given space is described by the noise reduction (NR) of the enclosure. The NR of an enclosure is defined as the difference between the sound pressure levels which occur at a position in the enclosed space with and without use of the enclosure (ref. 150). The noise reduction should not be confused with the transmission loss

(TL), which is defined as the difference between the acoustic power level incident on one side of an infinite panel and that transmitted through the panel. The NR depends on TL and acoustic properties of the receiving space.

Traditional acoustical engineering calculations of an enclosure NR are based on the TL of its walls. However, the TL concept does not apply for panels whose dimensions are smaller than half an acoustic wavelength. At low frequencies the acoustic half-wavelengths become so large that they exceed typical major spacecraft structural dimensions; this "low-frequency" range is the one considered in this report. The exact extent of this frequency range clearly depends on the size of the structure being considered. For the Apollo Command Module, with a typical dimension of the order of 10 ft, the flow-frequency range encompasses all frequencies below 55 Hz. For an electronic subassembly having a dimension of the order of 1 ft, this frequency range extends from 0 to 550 Hz.

Low-frequency sound may cause discomfort or injury to personnel or may interfere with task-performance efficiency. Such adverse effects appear to be associated with resonances of the human body between 2 and 20 Hz (ref. 147). Some of these resonances are primarily due to body masses vibrating in combination with muscular and tendon compliances. Others involve acoustical elements, e.g. the diaphragm may resonate with air cavities within the lungs. Criteria for vibration and sound environments for trained astronauts have not been fully established at this time.

Probably the most important adverse psychoacoustic effect of the low-frequency noise is its interference with speech communication (ref. 148). The entire acoustic spectrum contributes to speech interference, of course, but low frequencies present a particular problem since they are not attenuated effectively by earphones or headsets. Recent psychoacoustic studies have also shown that high-level low-frequency noise can have a masking effect over a frequency range which extends several octaves above the noise range. This effect is known as "the upward spread of masking."

The purpose of this report is to present an approach for predicting the low-frequency noise transmission of spacecraft structures on the basis of a series of experimental and theoretical analyses. The approach developed here should aid the spacecraft designer in estimating the low-frequency noise reductions he may expect, and should provide him with sufficient insight into the processes of sound transmission at low frequencies to enable him to avoid spacecraft designs which will have ineffective acoustic isolation at low frequencies.

Many of the calculations and discussions in this report refer to an acoustic model based on the Apollo Command Module (CM). This module is typical of spacecraft that have been built at this time, and it is likely to be a prototype for others to come. However, this report is not just concerned with the Apollo CM; rather, it is concerned with developing a more general, widely applicable acoustical model of axisymmetric spacecraft of a single- and double-shell configuration.

Data to be obtained from laboratory and flight tests of the Apollo CM should prove extremely useful for further study of many of the notions presented in this report. One may hope for some agreement between the field data and the analyses presented here. However, for any process as complex as sound and vibration transmission in complicated build-up structures, the process of model development must be a continuing one. Although many aspects of the models developed here are expected to shed light on the test data, the test data are equally expected to suggest modifications and changes in the models. . . .

We build up a conceptual model of low-frequency sound transmission from a series of theoretical and experimental analyses, which are intended to emphasize various aspects of the structural and acoustic behavior of a spacecraft. In the analysis of model systems, some of which differ in appearance quite markedly from the actual spacecraft, we indicate the limitations of each model (i.e., the deviations of the ideal model behavior from the actual), and we indicate the additional effects that must then be included. Such a model development procedure is fairly commonly used in architectural acoustics, where many competing effects can occur; it is of the utmost importance for the engineer to know over what frequency range and under what conditions each of the competing effects will have dominance.

It is also an important function of this report to suggest acoustic models and experiments for testing some of the concepts developed. Choices of such models (some of which may be similar to small-scale models which we have studied) are indicated when appropriate, based on experience gained in our test program.

Some of the major conclusions of this study are summarized below:

1. Over an important portion of the low-frequency range the noise transmission of shells is controlled by their "quasi-static" acoustic compliance. The compliance of curved and dome-like shells tends to be membrane-controlled. Such shells tend to be much stiffer than flat shell segments, the compliance of which is primarily flexure-controlled.

2. Acoustic resonances of contained spaces may occur. In the Apollo Command Module, the space between the two shells is narrow and long (as measured between the two poles of symmetry). It thus permits the occurrence of a low-frequency resonance which may drastically reduce the low-frequency NR.

3. When flat segments are present, and when curved shells are interrupted by relatively stiff reinforcing members, volume displacing structural resonances will occur at low frequencies. These resonances will be deleterious to noise reduction since they produce "volume pumping" and compression of the contained volume. The spacecraft design should avoid volume-pumping structural resonances below the frequency of the first acoustic mode of the contained volume.

4. Acoustical resonances between the venting system and the structural and acoustic elements of the spacecraft may occur. The importance of such a resonance in affecting NR will depend on the resonance frequency and on the efficiency with which the exterior low-frequency sound field can 'drive' the resonance.

5. Well-thought-out experimental analysis is an important adjunct to any acoustical-structural problem. This study shows that this is particularly true in the case of sound transmission, where many competing effects are present. Noise reduction experiments which are regarded only as proof tests, or as verification of a theoretical analysis, will not be so effective or so illuminating as tests which attempt to sort out competing vibrational and acoustical effects and to rank-order these in importance for the particular structure under consideration.

In a sense, design for good low-frequency noise reduction involves much the same considerations as design to contain the pressure in the spacecraft. The basic compliance analysis presented in Chapter III is closely related to the pressure vessel analysis that is required for predicting the structural integrity of the vehicle. There are subtleties in the acoustic design, however, that are not present in the mechanical structure design. These have to do primarily with the occurrence of structural and acoustic resonances that can severely diminish the NR provided by the structure. It is these resonances and their associated effects that we have tried to catalog and analyze in the discussions of this report.

The transmission of sound is a complex problem. At all times, it is worth reconsidering the inclusion of experimental analyses of potential designs in any spacecraft development program. Acousticians, faced with the problems of predicting the acoustical behavior of rooms and the sound transmission properties of walls, learned long ago to couple their calculations with model studies and well-thought-out experiments. A similar development in the field of space vehicle design would result in a great improvement of our understanding of the basic processes at work in such structures and perhaps result in a significant improvement of the acoustical and vibrational behavior of these systems.

ACOUSTIC FATIGUE

A report on acoustic fatigue (ref. 151) contains discussions of some tests made on the fatigue of thin panels. In these tests, panels were subjected to discrete-frequency noise from sirens and to random noise generated by a very large compressed-air jet. Sound pressure levels varied from approximately 140 to 161 dB. The panels were mounted in various ways, some flat and some curved. The tests were conducted at different static-pressure differentials between one side of the panel and the other. The flat panels were either bolted in place or bonded on one or both sides with a sandwich bond through the mounting surface. The curved panels were bolted in place either with a sharp-edged molding conforming the inside radius of the panel to the flat mounting plate or with a radius on the edges of the conforming molding.

The results of the acoustic fatigue tests in the report can be summarized as follows:

1. Increases in time to failure (better fatigue performance) were obtained with increased panel thickness, increased panel curvature, and particularly increased static-pressure differential across curved panels.
2. The structural failures produced were similar in nature for both the discrete-frequency and random-loading tests.
3. At a given rms stress, the times to failure were generally shorter for the random loading than for the discrete-frequency loading. These differences in failure time were noted to be a function of stress levels, the larger differences occurring at the lower stress levels.

4. The role of discrete-frequency testing in these simplified structure designs appeared to be directed toward the location of weak points in the design, since with this loading, quantitative prediction of time to failure was almost impossible. Random loading time to failure was much more predictable.

A variety of laminated structures are being applied successfully throughout industry to solve problems caused by excessive mechanical vibratory disturbances. Relatively little information, however, has been compiled on the resistance of such structures to sonic fatigue. Because of the concern of the aerospace industry with the effects of severe acoustic loadings on airframes produced by jet engine noise and boundary-layer noise in high-speed aircraft, the response to acoustic fatigue loadings of laminated aluminum viscoelastic panels at normal temperatures was investigated (ref. 152). As part of this work, viscoelastic test panels (24 by 24 in.) were constructed from 0.020-in. aluminum (2024-T3 Alclad) facing sheets with a 0.020-in. viscoelastic interlayer. Aluminum "control" (reference) panels were made from 0.051-in. aluminum sheets. The panels had two stiffeners riveted to both types of sheets, resulting in a three-bay construction. Earlier test sections had cross stiffeners added to the two mentioned, but much fatigue failure was observed at the fastening point of these stiffeners. The final construction used consisted of "hat"-section aluminum stiffeners with hard maple plugs driven in the ends for damping.

In these investigations, a broadband siren, with irregularly slotted rotors to modulate an air stream, was used as the sound source. Four different rotors were simultaneously driven at the same speed throughout a given test, producing a broad noise-like spectrum of sound. Commercial condenser microphones were used, and each was checked daily with a calibrated portable acoustic source. Absolute preliminary calibration of each microphone was made in an anechoic chamber. Strain measurements were made by instrumenting each panel with a maximum of six metal-film strain gauges. Microphone and strain-gauge signals were recorded, and copies of the recordings were formed into loops and analyzed with a harmonic analyzer and a probability density analyzer. The general conclusions drawn from these investigations were:

1. Comparative fatigue data indicated that the viscoelastic panel has a longer sonic fatigue life than an aluminum panel of equivalent weight by a factor of 1.58 at 160 dB SPL, 3.5 at 157 dB SPL, and 6.0 at 154 dB SPL.

2. Sonofax records of the pre-test and post-test panels in-

dicated that acoustic excitation did not weaken the internal bond or produce an unbonded area. In some cases, riveting operations had introduced a minute unbonded area around the rivet head before the tests, especially noticeable in the panel that was highly dimpled. Sonofax records of all the viscoelastic sheets (prior to construction) showed a generally good condition of the bond except for three sheets in which a small unbonded region was detected near the panel edge. An attempt was made to locate these areas in the position where a fatigue failure was not anticipated.

3. The scattering of the fatigue data was generally quite small. This was particularly true for the aluminum panels. Viscoelastic panels showed good correlation of results at 160 dB SPL; at 157 dB SPL and 154 dB SPL, however, scattering was more pronounced. By averaging the time-to-failure data it was possible to establish a reasonable pattern of difference between the fatigue curves for the viscoelastic and the control panels.

4. All fatigue failures occurred on the back of the panel (away from the sound field) near the flange rivet line in the bay area farthest from the sound source. The cracks would generally emanate from a rivet and progress in a downward or upward direction (at right angles to the direction of arrival of the sound energy). Several cracks developed ¼ to ⅜ in. from the rivet center line.

The testing of simple aircraft structure elements by the use of either a broadband siren, an electromechanical, or an electropneumatic sound transducer as described, gives some useful information about the effect of heavy acoustic loadings on the fatigue of such structures. However, there are many ways in which this test method does not simulate the circumstances under which fatigue will occur in a high-speed aircraft or space vehicles. In a recent paper (ref. 153), several members of the staff at the University of Toronto discussed this failure of simulation. In these investigations, the conventional sound source problem developed from the convective decaying pattern (observed in the near field of the jet) was simply not simulated by a siren, because the siren produced only acoustic effects and not the acoustic-related turbulent-flow effects that create the noise at the exit of the jet. A similar criticism of the siren's failure to simulate the pressure field beneath a turbulent boundary layer was also made. The failure of simulation was primarily because the convection speed of the transducer-produced eddies is the same as that of sound, whereas the convection speeds of the pressure patterns in a jet are only related to the flow speed.

Another objection to the source of pure sound for testing was that the correlation distance for the operation of any given small sound source is limited to the dimensions of acoustic wavelengths, whereas in true jet or boundary-layer noise this correlation distance corresponds to the eddy size which is very much smaller.

As part of this work, two pin-hole microphones were placed in a plate against which a jet was allowed to strike. Somewhat simple instrumentation was used, with capacitor microphones driving a conventional commercial sound-level meter. Correlation techniques of a rather standard type, working on tape recordings of the results, were employed, and a commercial spectrometer obtained curves of spectral density for various test conditions. The test plate was oriented at varied directions with respect to the jet and measurements were made. The results can be summarized by the following quotation from the concluding remarks of reference 153.

> It seems evident from the present investigation that the impinging jet arrangement may be used for structural fatigue studies to replace either parallel jets or a turbulent boundary layer. However, the radial-type flow near the jet center line at normal impingement may not simulate the proper coincidence effects. One might have to sacrifice the largest enhancement of rms pressure level found for that circumstance and go to more oblique impingement or away from the jet center line to obtain a more parallel flow condition.

In the above quotation "largest enhancement" refers to the fact that the nondimensional rms pressure measured with normal impingement is very much higher than the rms pressure under a turbulent boundary layer. Although this enhancement is reduced for oblique impingement, it still remains quite high, and the jet, therefore, is an extra severe test or an extra good simulation of the true jet acoustic fatigue situation.

In relating this work (ref. 153) to the nonaerospace field, it should be emphasized that a piece of metal other than a jet deflector is seldom required to operate directly in the exhaust stream of either a turbojet aircraft or a rocket. However, the better the jet simulates the boundary layer, the more applicable is this method of testing to the fatigue situation encountered in the high-speed movement of a jet aircraft or space vehicle. Thus, since boundary layer fatigue might be encountered in an industrial high-speed gas flow process, this approach may be suited to testing fatigue under these nonaerospace conditions.

In reference 154, Hardrath discussed primarily nonacoustic fatigue matters, but he also gave a general survey of acoustic fatigue research in the United States. The data in the report indicates that the main effort of NASA in acoustic fatigue is directed toward defining the acoustic environment generated by large booster engines and by supersonic flight in the atmosphere. Emphasis was placed on the effects of intense noise at frequencies below 50 Hz, including subaudible frequencies. Information in the study implies that it is more difficult to define the nature of the environment than to design a test to simulate that environment. Hardrath also discussed the attempts to simulate simultaneously the acoustic, vibrational, thermal, and pressure environments of a spacecraft during lift-off. This effort demonstrated that correct simulation of an environmental stress of this type must necessarily involve all the stresses being applied simultaneously.

CHAPTER 5

Tests, Measurements, Analyses, and Instrumentation

NASA had to devise and conduct a variety of large-scale complex tests to develop the tools needed for its space program. For example, a Saturn V test tower was constructed and equipped with an 8-ft-diameter water main to feed water to the jet deflector, fed in turn by 13 individual 3-ft-diameter mains, each draining a 100,000-gal tank. Large acoustic facilities were also built for testing whole sections of the Saturn rocket in intense sound fields. Since such extensive tests and facilities may not be closely related to operations outside of NASA, this chapter will be restricted to less spectacular operations but will include measurement and analysis techniques and specific instrumentation that may be of interest to the nonaerospace community.

HIGH-INTENSITY ACOUSTIC TESTING

High-intensity acoustic testing is described in this section. In the development and flight qualification of unmanned spacecraft, Jet Propulsion Laboratory (JPL) exposed the vehicles to high-intensity sound to simulate the effects of boost and passage through turbulence-inducing regions of the upper atmosphere. The high-intensity acoustic test unit constructed at JPL (ref. 155) was designed for both reverberative and progressive-wave sound testing, the largest element being a 1000-cu ft pentagonal reverberation chamber large enough to test complete unmanned spacecraft. The chamber is about 12 ft high by 5 ft in bisecting diameter, providing a volume about ten times as great as the hardware tested. In addition, a 7-cu ft reverberation chamber for smaller objects, a 1-ft-sq progressive-wave tube, a 7-in.-sq progressive-wave tube, and a 2-in. diameter progressive-wave tube were constructed. Both electrodynamic and electropneumatic noise generators can be used in this facility. Electrodynamic drivers were used for the 5 to 10-W acoustic-power range and electropneumatic devices for the 2-kW acoustic-power range. The energy needed by the electropneumatic noise generators was produced by a 200-hp aircompressor, which supplied air at 300 standard ft^3/min at 40 psig. Seventeen acoustic horns of assorted sizes and shapes were employed to couple the generators to the test areas. Rather conventional microphones and calibrators were used in the control and monitoring system, the majority being of the condenser type with two semiconductor microphones for the higher sound-level ranges. Pistonphones, electrostatic actuators, and reciprocity calibrators were used to calibrate the microphones and a typical collection of acoustic source and measuring equipment completed the installation.

The 1000-cu ft reverberation chamber, in which electropneumatic drivers were used, can produce flat random noise in a range of 125 to 1600 Hz with an acoustic level of 158 dB. This spectrum can be shaped since the drivers can produce noise from as low as 5 Hz to as high as 8000 Hz. Using electrodynamic drivers, discrete frequencies from 400 to 8000 Hz can be produced at a noise level of 132 dB and random noise from frequencies about 500 to 7000 Hz at a level of approximately 138 dB. In the 7-cu ft reverberation chamber, random noise levels up to 145 dB and discrete sound levels up to 150 dB are achievable. In the progressive-wave tubes, levels of the order of 145 dB are also achievable, with random noise levels as high as 167 dB being achieved in the 7-sq in. tube. In the 2-in.-diameter plane-progressive-wave tube, random noise levels as high as 181 dB, and sine wave levels up to 171 dB are possible.

In the JPL installation, instrumentation and data acquisition systems have up to 100 data acquisition channels, including those for accelerometers, strain gauges, and microphones. Each

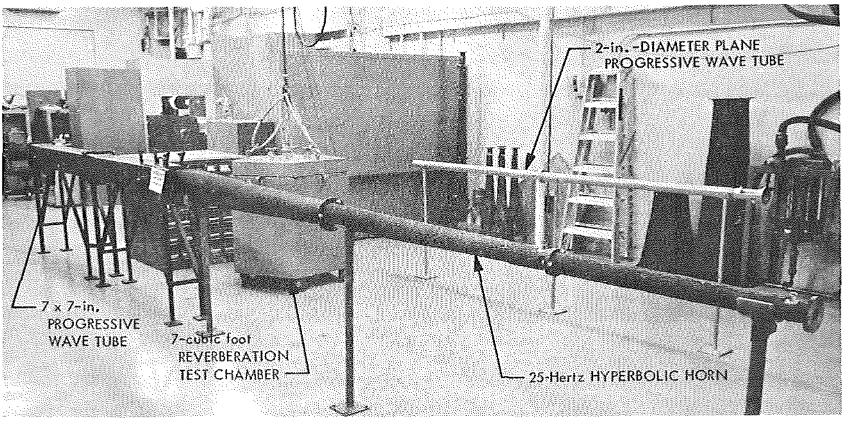


FIGURE 23.—Acoustic test system.

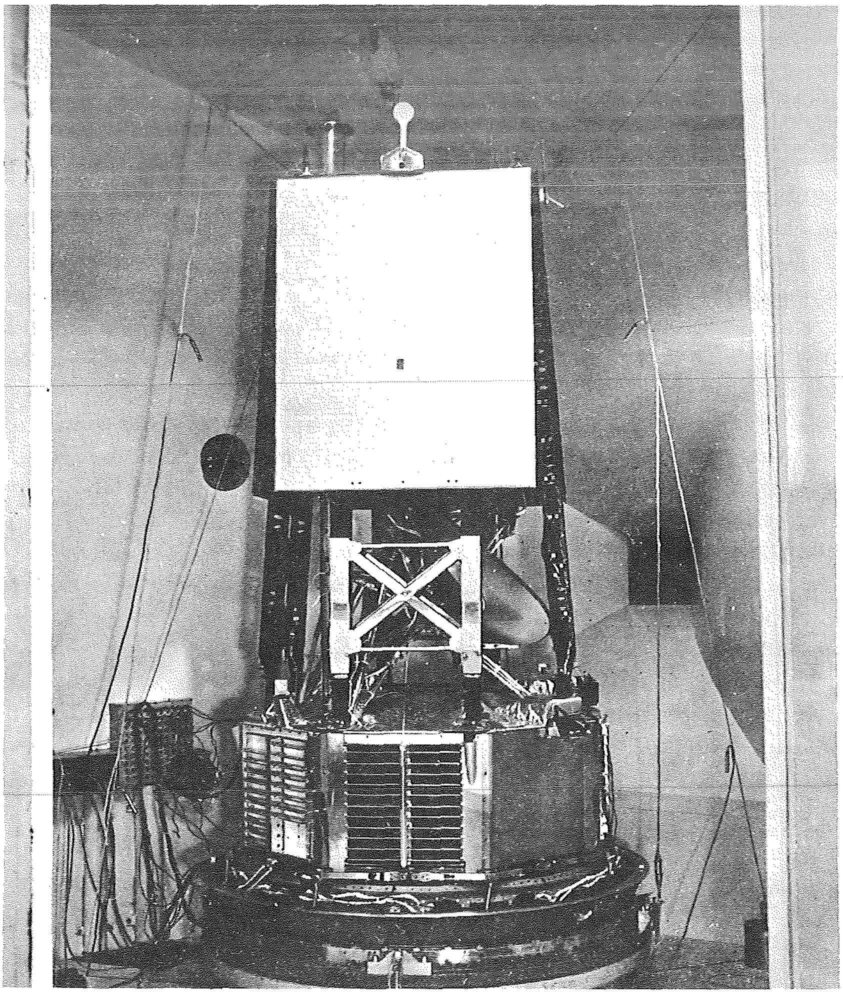


FIGURE 24.—Mariner Venus 1967 structural test model.

channel includes the required transducer signal-conditioning and recording equipment. Acoustic test equipment used at this installation is shown in figures 23 and 24.

Another type of an acoustic test facility was recently built at Langley Research Center. This unit operating in a frequency range of from 1 to 50 Hz can determine the possible effects of low-frequency noise associated with the launching of large spacecraft. It is of general interest because of its capability to solve some complex problems involving an extremely massive loudspeaker system. The facility is also useful for simulating some aspects of sonic boom. The construction of the chamber and loudspeaker and the performance of the facility should be of interest to nonaerospace groups. This Low-Frequency Noise Facility (LFNF) (fig. 25) is described in reference 156. Some of its primary components are illustrated in a cross section in figure 26. The facility consists principally of a cylindrical test chamber, a large loudspeaker in one end of the chamber, and a movable tuning wall that can be positioned to close the opposite end of the chamber. It may be operated with the chamber either opened or closed. The LFNF is large enough to accommodate both small buildings and space vehicles of the Apollo command-module class; manned vehicles and individual human beings can also be tested in it.

The outside dimensions of the LFNF are 30 ft long by 27 ft in diameter. A building 10 ft by 30 ft, housing the hydraulic system and control room, is attached to the basic facility. The test chamber has relatively stiff walls with the natural frequencies above the top operating frequency of 50 Hz. It is fabricated of 1-in. steel, rolled and welded to form a continuous shell structure, stiffened by 18-in. T-rings of 1-in. steel on 48-in. spacings along its length. Longerons of similar construction were welded between the rings at spacings of 24° around the cylinder. The movable tuning wall, also of heavy steel construction, is installed on railroad-type tracks, counterweighted, and equipped with locking devices to prevent tipping or moving from a locked

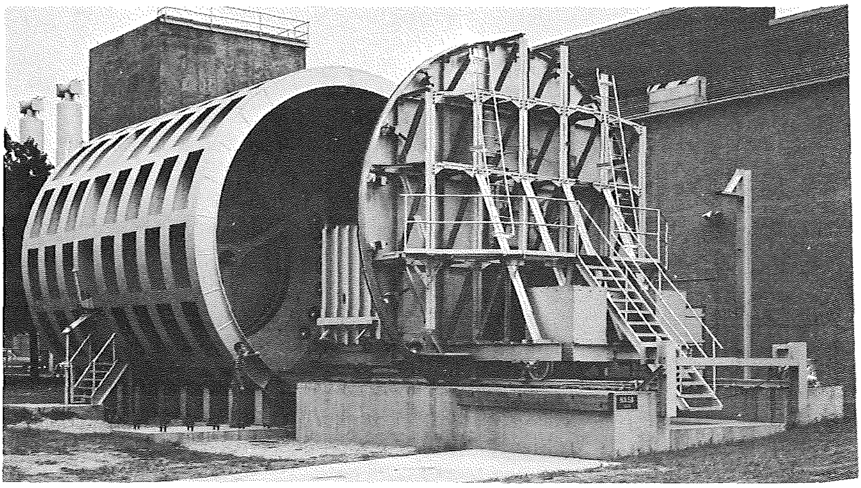


FIGURE 25.—Langley Low-Frequency Noise Facility.

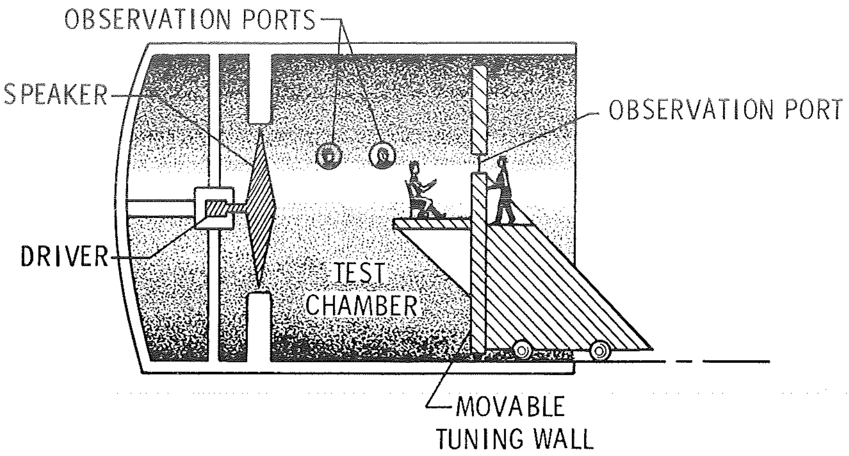


FIGURE 26.—Cross-section of the Langley Low-Frequency Noise Facility.

position. The wall, weighing 26 tons, is moved by a cable system operated by an air winch. The wall is equipped with a pneumatic seal.

The aluminum-honeycomb, 14-ft-diameter loudspeaker has a high stiffness with a natural frequency well above the facility operating frequency. It is shaped like a double cone, 2-ft deep through the center. The core consists of a 3 lb/cu ft honeycomb and a 0.040-in. skin is autoclave bonded to the core. This construction minimizes weight while providing the necessary stiffness. The outside of the loudspeaker, which is driven as a piston, is provided with an adjustable Teflon seal that provides $\frac{1}{16}$-in. clearance from the adjacent Teflon surfaced wall.

The electrohydraulic driver of the LFNF is primarily a piston with an 8 in.^{2} area that has a maximum axial stroke of 9 in. The hydraulic pressure (maximum of 3500 psi) is electronically controlled by a system in which the desired acoustic effect is obtained by putting the necessary electric inputs into the system with a function generator such as a discrete-frequency oscillator, a playback of a random signal recorded on tape, a momentary closing of a physical contact, etc. The input electric signal is fed into a computer circuit that forms part of a servo-loop controlling the operation of the hydraulic valving of the driver. A wide variation in acoustic environment can be thus produced in the chamber within the frequency range of the driver. This driver, however, has limitations which confine the operation of the facility to the frequency range shown in figure 27. The mo-

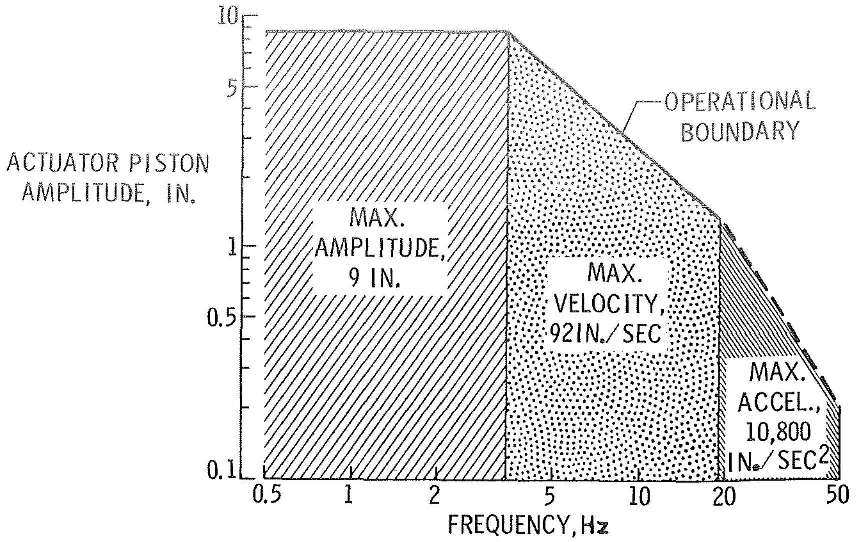


FIGURE 27.—Design operating range of the hydraulic driver for the Langley Low-Frequency Noise Facility.

tion is limited only by the 9-in. stroke until a frequency of 3.3 Hz is reached. Above 3.3 Hz there is a velocity limitation of 92 in./sec to a frequency of approximately 19 Hz where the operation is limited by acceleration brought about by high inertial forces. The amplitude and velocity limitations are fixed but the acceleration boundary can be extended to higher amplitudes by a technique in which air springs in the test chamber are used for the inertial balancing of the electrohydraulic driver.

In the initial tests of the LFNF chamber, noise levels of about 160 dB were obtained at frequencies below 3 Hz with a drop-off in level to 140 dB at approximately 20 Hz. Above 20 Hz the movable wall provided a tuning capacity that resulted in levels on the order of 155 dB in the frequency range from 30 to 50 Hz. A potential for higher acoustic levels has been recognized and techniques for obtaining them have been considered. Studies indicate that potential levels of 165 to 170 dB over the 1 to 50 Hz operating frequency range may be obtained.

This facility has been used to test building structures and examine the effect of low-frequency noise on man. The study of the effects on human beings has been mainly limited to astronauts. The effects on structures of sonic boom and lift-off noise also have been studied in the LFNF.

FATIGUE TESTING

In another section of the survey in which fatigue effects of intense sound fields on structures were considered, basic methods for testing acoustic fatigue were discussed in connection with the experiments described there. It appears appropriate at this point, however, to discuss the validity of specific test methods. In reference 157, Lyon discusses the problem of simulating the total noise effect of a turbulent boundary layer on a structure by applying only an acoustic field. Ideally, proper simulation would mean the reproduction of the complete distribution of acoustic pressures over the structure with correlation and convection properties approximating the turbulence. In a sound field the speed of propagation, wavelength, and frequency are related. However, a turbulent field differs where a particular wavelength component may have a wide distribution of frequencies and/or convection speeds, making it questionable as to whether the acoustic field gives adequate simulation.

In respect to vibratory response, the turbulent energy at wavelengths near the free bending wavelength in the panel accounts for most of the excitation. Simulation of loads is still not possible, even by restricting the simulation to the small group of wave numbers near the bending wave number, since the acoustic frequencies of these wavelengths would generally be higher than the frequencies in the channel. When the excitation of a panel and its consequent fatigue are the significant factors, it is quite possible to simulate, with a purely acoustic field, the effect of the turbulence. Notwithstanding, the corresponding sound transmission through the entire structure might not actually be properly simulated because it depends on the nonresonant or force motion of the structure. The panel response itself, being basically a resonance phenomenon, is relatively easy to simulate.

Lyon also discusses (ref. 157) three categories of modal behavior as far as excitation by convected turbulence is concerned. He indicates that one of these occurs when the modes move slower than the convection speed, another when they are moving at the convection speed, and one when they are moving faster than the convection speed. He refers to these as hydrodynamically slow, coincident, and fast. In addition, he indicates that simulation of the power input from high-speed turbulence is primarily a matter of simulating a wave number spectrum. The analysis shows that the spectrum is quite smooth, having roughly a 10 dB variation over one to a half decade in wave numbers or three decades in frequency.

After a discussion of the general subject of the response of a simple structure to that of a supported panel, Lyon proceeds to describe how the radiation efficiency of the panel can be used as a measure of the response, and then outlines which of the various convection rates will have the greatest effect on the panel. He points out that the basic difference between different modes of excitation of the panel requires the consideration of the direct and reverberant vibrational field. The direct field resembles a direct wave entry in a sound field, and it is the free wave which is generated, disregarding the additional wave components created by structural discontinuity. The reverberant field, which contains most of the energy, is produced by successive reflections of the direct wave energy from the edge of the panel. The energy in the panel will normally make several passages across the panel before it is dissipated.

In summary, the vibrational field of structural panels driven by broadband noise appears to be highly reverberant, and somewhat insensitive to the precise nature of the disturbance. Therefore, simulation may be possible if the required power levels in the various frequency regions can be supplied by this sound field. Lyon concludes with a discussion of the problem of predicting the spectral properties of turbulent pressure fields. It should be noted that measurement of these fields with a fixed microphone provides a completely different result than the real power input spectrum delivered by such fields to a panel. In fact, the spectrum measured by a fixed microphone might be as much as 25 times broader than the actual exciting spectrum.

METHODS OF DATA ANALYSIS

The Wave Analysis Section, Measurement Systems Division, Kennedy Space Center analyzes and reduces all the analog information (such as vibration and acoustic data) recorded during the launching of large space vehicles or during static testing of vehicle engines and equipment. This service is also provided to other NASA facilities responsible for vehicles, launches, or tests. The following forms of analyzed data are presently available (ref. 158):

1. Wideband (raw data) oscillograph records.
2. Overall rms-amplitude-vs-time charts.
3. Octave or one-third octave-band amplitude-vs-time charts.
4. Spectral and correlation analysis.
5. Probability analysis.

Although the specific activities of the Wave Analysis Section are too complex to discuss in detail here, the following general description may prove useful. The acoustic analysis made by this section involves the simplest tests of overall time-history analyses in which sound-pressure level is recorded as a function of time. The same function can be performed for one-third-octave bands within the total acoustic spectrum. Complete spectrometer plots of sound pressure level vs frequency for any given time can be made with a one-third-octave frequency analyzer. The same type of analysis for vibration is also possible, but more complex analytical procedures are required. The present equipment of this section provides power-spectral-density plots and cross-spectral-density plots in terms of either cospectrum or quadrature-spectrum. In addition, the transfer function in linear amplitude vs frequency can be plotted. This section conducts detailed analyses with a "time-compression" frequency-swept narrow-band analyzer, including the detailed examination of a portion of the vibration record. Most of this data can then be transferred to computer-compatible tape. The more sophisticated and analytical efforts of this section, however, are directed to vibration rather than acoustic matters.

In an extension of the type of analysis just discussed, Newberry gives a detailed description of the techniques for analyzing random vibration data by computer (ref. 159). Although frequency ranges and intensities differ in vibration and acoustic matters, the techniques appear applicable to some forms of acoustic analysis. This detailed report includes the exact process by which such an analysis is put into a computer and how the results are obtained.

Another type of analysis is described in reference 160. This report gives calculations and tabular data generally useful for octave or fractional-octave spectrum analysis in any field. It also includes techniques for combining the individual dB levels in constant bandwidths into an overall sound pressure level, for determining the octave levels in one octave-band system when the levels in a differing octave-band system are known, and for determining one-third-octave levels when the octave level and the dB/octave slope is known. As described in this report, the technique to combine dB levels of two bandwidths involves using a chart or curve with the dB level difference of the two bandwidths and deriving therefrom the increment that must be added to the higher level to give the net total level. To determine one-third-octave levels when the octave level and the dB/octave slope is known, a table is entered for the increments to be added to or subtracted from the octave level to give third-octave levels. The technique for shifting between two sets of octave bands involves the use of a table that can be replaced by two curves plus two other tables. This technique was designed primarily for converting between the "old" and "new" ASA-designated octave frequency bands.

SPECIALIZED INSTRUMENTS

A specific analytic instrument called an acoustic spectra comparator recorder (ASCOR) has been constructed that may be of interest in spectrum studies outside the aerospace field (ref. 161). The instrument has several modes of operation. In the "record" mode, a commercial spectrometer is scanned through the frequency range involved and the output recorded on an x-y plotter. This plot represents the spectrum intensity of an unknown input signal. In the "compare" mode, the desired or reference spectrum level is set by means of adjusting knobs located on the long panel. The actual measured level in each of the one-third octave or octave bands is then compared with the reference spectrum and the difference indicated on the null meter. This reading is the difference in dB between the desired and actual sound pressure level. The instrument can be manually stepped from one spectrum range to the other and the difference observed visually on a meter, or it can track through the entire range automatically and record the spectrum errors on the x-y plotter. It has served primarily as a controller for a NASA acoustic testing facility, allowing a manned spacecraft or one of its elements to be subjected to controlled noise spectra. The general principle of the instrument is, however, applicable to many other testing situations.

In the instrumentation for the rocket grenade experiment some very interesting problems were encountered (ref. 101). The experiment involved detecting and recording sound arrival from grenade explosions thousands of miles away. The most significant problem in such an experiment is that of providing an adequate signal-to-noise ratio at the receiving microphone. In each test, the microphones have to give usable indications of arrival times from 12 grenades which are exploded successively as the rocket attains higher altitudes. At the highest altitudes, the acoustic signal is quite small and very good sensitivity is needed. The microphones respond to the relatively narrow frequency range of about 1 to 10 Hz. The primary noise disturbance is that of wind and turbulence.

The microphones in this experiment were invariably located in relatively isolated spots (Point Barrow, Ascension Island, and Wallops Island) where the normal ambient noise level was created entirely by natural phenomena. Because most of these places were windy, it was necessary to protect the microphones from the noise of the wind. Two types of microphones were used: (1) a capacitor and (2) a hot-wire microphone. The condenser microphone has a very loosely-mounted diaphragm so that, even though it is a stiffness-controlled device, its basic frequency range (up to diaphragm-mounting resonance) is relatively low. The hot-wire microphone has long been employed for such applications as locating gunfire by triangulation in which the arrival times of the shock waves from artillery explosions are used to establish accurate baselines for a system of triangles. It is based on the principle that the changes in air velocity with the arrival of sound waves cause sudden cooling of the wire, which is interpreted by external circuitry as a change in wire resistance.

The natural surroundings in some of the sound receiving locations helped reduce the noise of the wind. Heavy forests appeared to act as a natural wind screen if the microphone was placed on the ground beneath the trees. At times, however, winds of high velocity caused such severe turbulence at the treetop level that the screening advantage was lost. Deep snow cover over ground-mounted microphones was also an effective wind screen, particularly in treeless northern locations. Three types of mechanical wind screens, constructed for the experiment, also gave limited protection. One, known as the "Spider," was made of 12.5-foot arms (tubes) that fed the acoustic signal from the place where it was picked up to the microphone. Although both stiff-metal conduit and rubber tubes were used in this screen, only the rubber tubes allowed spacing of its tips to be easily changed. In a test of this noise reduction scheme, a comparison was made of the results of either separating the tips of the Spider as far as possible into a circle 25 ft in diameter or bringing them together so that they were all within a circle 6 in. in diameter. The noise reduction was essentially the same for both arrangements.

The Spider concept implied that if the turbulence generated at the individual tube tips of the microphone was completely random, the noise of this turbulence would increase on a power (random) basis whereas the desired signal acoustic pressure would increase directly. In the tests, however, very little noise reduction was observed. One possible explanation may be that low-wind conditions (under 8 mph) create little or no natural turbulence. The turbulence (or noise) indicated by the standard microphone is created by the introduction of the neck of the microphone into the airstream; this turbulence appears not to extend very far from the neck. The cancelling effects of the Spider applies as well to this type of turbulence as to natural turbulence. If the noise received at the tip of each Spider arm was caused by the tip, then the spacing of the tips would make no difference.

Another wind screen used in the rocket experiment was designated "Ike." It consisted of three concentric hemispheric frames covered with copper screen, 2, 2.75, and 3.5 ft in diameter, which gave a higher improvement ratio at low noise levels (under 0.3 dyn/cm) than the Spider. At high noise levels (0.6 dyn/sq cm), there was less improvement in the signal-to-noise ratio. The third type of wind screen consisted of horsehair matting 2 in. thick, which was formed into a tube with a closed end, 1 ft in diameter and 2 ft high. In a later test, an additional cover was added, also 2 ft high, but 2 ft in diameter. Still later, a third cover was added with the same height but 4 ft in diameter. The addition of a second cover considerably improved the performance of the Ike, but the third cover had relatively little effect. In the tests conducted at Point Barrow the two-cover wind screen was used.

Apparently these mechanical wind screens operate on the principle that they suppress noise by preventing the wind from reaching the microphone, thus reducing the turbulence. Supposedly, when the wind is blocked, noise is created over the surface of the screen. Best results were obtained when this cover was a foot or more from the neck of the microphone. At wind speeds of 10 or more mph, however, a difference is noted in the effect of the spacing of the Spider tips. The larger-diameter spacing reduced noise more than the lower-diameter ones, indicating that the presence of large-scale turbulence was probably caused by natural phenomena. The microphone-screening devices likewise began to lose their effectiveness as the size of the turbulent wind eddies approximated the cover in size.

It is interesting to note that although the Spider type of wind screen can reduce the noise level under severe conditions, it has little value for the rocket grenade experiment. Its greatest usefulness is under conditions so severe that the achieved reduction still does not make the noise level acceptable. Thus, it would be necessary to reduce the noise at the microphone to a background of about 0.1 dyn/sq cm in order to record all 12 grenades. On the other hand, the horsehair covers are most efficient in this range and could make bad and marginal situations usable. In theory, microphones fitted with horsehair covers should allow recordings of sound from firings with good results in winds not exceeding 8 mph. Unfortunately, winds at many receiving points exceed this limit.

CHAPTER 6

Acoustics for Nonacoustic Functions

Acoustic methods have long been used for functions in which sound or sound-like phenomena were not ends in themselves. Examples of these functions include (1) magnetostrictive-delay lines (based on acoustic-wave-propagation time producing the delay), (2) sonic and ultrasonic transmission probing of the integrity of mechanical structures, (3) indirect analysis of the noise produced by mechanical devices to determine their modes of operation, and (4) acoustic-leak detection (depending on the sound produced by leaking substances as they escape through narrow openings). Some specific applications of these methods are discussed below.

ACOUSTIC DETECTION

In a large, liquid-fuel booster for a space vehicle, the system that supplies fuel and oxidizer to the combustion chamber must be extremely reliable and deliver the liquids at a very high speed. Typically, 5000 gal/min of the working fluids must be pumped by flawless high-speed pumps. To meet such high performance requirements, an external evaluation pump action that warns of incipient pump failures was investigated (ref. 162).

The report may be summarized briefly as follows: An analysis of frequency of a spectrum of the noise signature of a cavitating pump system shows a number of definitive patterns that may be associated with physical phenomena. At least one pattern appears to be closely associated with head loss (loss of delivery pressure). The associations between patterns and phenomena, however, were largely based on subjective observations. The major utility of the suggested technique was one of exploratory diagnosis and no semiautomatic warning of pump failure could be expected from it. Nevertheless, it is a useful tool for analyzing pump performance.

Several related methods for indicating pump failure were also suggested in this report, including a bubble detector sensitive to both bubble size and number, which might transmit acoustic energy through a two-phase mixture to a receiver. As stated by the authors—for a particular input frequency (bubble size) at a known total pressure, the transmissibility of the signal would also be dependent on the number of bubbles.

A more common application of acoustic detection (detecting leaks in gas systems) is described in an Ohio University report (ref. 1963). The investigation made by this institution was divided into three tasks: a complete literature search of leak detection methods, a complete survey of available state-of-the-art detection devices, and the improvement of some of the existing detection methods.

As a result of this study, several methods of acoustic detection evolved. A promising one involved the injection of 400-cycle sound energy into a gas system. The sound energy leakage, detected by cross correlation, gave inconclusive results since the sensitivity ranged from zero to extremely high values. This method was originally investigated by Mine Safety Appliances and discussions between personnel of this company and the Ohio University group disclosed that various difficulties were predictable. The amount of acoustic energy needed might be extremely high, and such acoustic leak detection methods would tend to identify any discontinuity (such as an elbow or a T in plumbing) as a leak even though one did not exist. The Ohio University group then attempted to modulate the leak rate by introducing pressure changes into the system to detect the effect of the pressure changes on the leak. Because most leaks generate a very-high-frequency noise type of acoustic energy, concentrated at about 40 kHz, this modulation method was tested by a simple amplitude detector operating in the same frequency range. This method should prove quite practical, provided a suitable transistor microphone can be developed.

Another acoustic detection method involved sonic and ultrasonic probing of material structures. For example, improvements in the strength-to-weight ratio of materials has resulted in the development of honeycomb sandwich materials. A significant problem associated with the use of these materials, however, is the difficulty in verifying their structural integrity in a nondestructive way. Clotfelter described some acoustic techniques for nondestructively evaluating the integrity of bonds in such composite materials (ref. 164). In his research, it was particularly significant that this integrity be accurately evaluated because he was dealing with the upper stages of the Saturn vehicle in which both liquid hydrogen and liquid oxygen are used. The following basic composite materials are discussed in this report:

1. *Bonded honeycomb construction consisting of metal face*

sheets adhesively bonded to a reinforced plastic honeycomb core.

2. The "double sandwich" construction consisting of metal face sheets, heat-resistant phenolic, and mylar honeycomb cores separated by a thin metallic vapor barrier and adhesively bonded together.
3. Foam materials adhesively bonded to metal.
4. Balsa wood adhesively bonded to steel.

In many cases, only one side of the investigated material is accessible, making the nondestructive evaluation of the bond very difficult. Where both sides are available, much simpler methods of evaluation can be used.

A method involving transmission through a panel in which either water or air coupling to the surface is used is described in reference 164. In the water-coupling method, ultrasonic energy from a driving transducer passes through water to one side of a panel and a crystal receiver is placed on the other side of the panel. When the transducer is excited with an ordinary oscillator and the received signal is processed by a reflectometer, the debonded areas in the sandwich are clearly detected. The report contains a description of frequency-scanning methods that can be used to determine quarter-wave and half-wave intervals through the honeycomb and a surface panel so that the exact depth of the debonding within a panel can be determined. In the air-coupling method, Clotfelter discovered that relatively low sound energy should be used and that it was feasible to place a single transducer in the middle of an empty tank and scan the outside with a receiver.

Methods for inspecting a single side of a panel were studied in considerable detail. A commercial swept-frequency one in which a device called a Coindascope was used appeared to be ineffective with insulating materials, particularly thermal insulating types. The extensive changes in mechanical impedance introduced by the composite structure of a honeycomb panel prevented satisfactory penetration by this method. Another one-sided inspection method involved coupling a transducer to a point on the surface of a panel and searching the remainder of the panel surface with a receiver. A good bond of panel to core absorbed sound, while the presence of debonded areas was indicated by sharp increases in the sound transmitted along the panel. The surface-wave method was modified by using a dual transducer-receiver unit with the two elements mounted close to each other. As the unit passed over a surface, areas of debonding caused a greater percentage of the incident sound energy from the transducers to be reflected into the receiver.

None of the preceding methods gives a clear indication of the debonding location, that is, on the near surface, the far surface, or within the core. A pulse-echo method was used to seek better depth information, but the received echoes were too small to give a clear indication. This method is particularly ineffective if burst pulses are used, but it is somewhat better for single pulses.

A combined detection method in which bursts of pulses are sent into material and the echoes examined for ringing has been developed. In this method, a search is made for the resonance of the materials causing the echo rather than for the strength of the echo. Since poor bonding leads to poor damping, a considerable resonance of panel components occurs when this pulse-echo method is used, providing good indication of the debonding location within the panel.

In reference 165, Dickinson describes another nondestructive acoustic method for analyzing the actual stress applied by a concentrated load to a mechanical structure. He indicates that the transmission of acoustic energy from a transducer to a receiver through a cylindrical thin-wall tube section makes it possible to determine where specific localized stresses were applied to the tube as well as to evaluate the intensity of the stresses. In this method acoustic energy is directed through paths with multiple reflection so that during the passage from the transmitter to the receiver, sound energy passes from one up to N times through the length of the test section. Each impulse of sound energy passes through the test section in a slightly different path, and an oscilloscope display indicates the energy received through each of these successive paths on which stress was applied. The arrival times of the impulses are separated by an amount equivalent to approximately one round trip through the system. The geometry of the system and the type of display are shown in figure 28.

An ultrasonic method of measuring the temperature of extremely hot gases also has been developed (ref. 166). The use of sound velocity to measure temperatures was suggested nearly a century ago, and significant work has been accomplished since then. In an ideal gas, the dependence of the velocity of sound on temperature is given by $v^2=\frac{\lambda RT}{M}$ where v is the sound velocity, λ is the ratio of specific heats, R is the gas constant, T is the Kelvin temperature, and M is the average molecular weight. If the gas composition is known, a measurement of sound velocity will lead to a determination of the temperature. Since this composition data is available for many gases at high tempera-

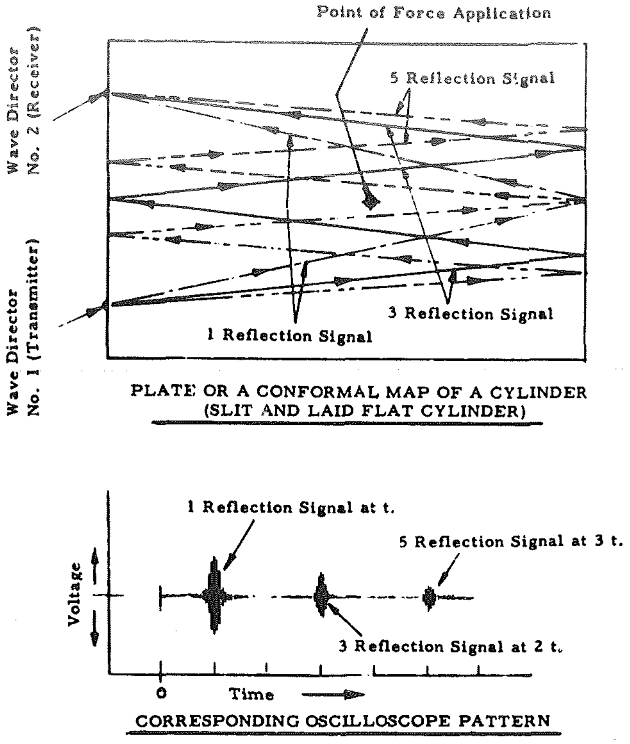


FIGURE 28.—Path of test signal through test panel and resulting scope display.

tures, sound velocity can be calculated as a function of temperature. In a real gas, consideration must be given to the frequency dependence of the sound velocity (important only for ultrasonic frequencies), which is caused by the finite relaxation time needed to adjust the internal degrees of gas freedom during an adiabatic acoustic compression. An absolute calibration of the high-temperature, high-pressure system for any particular gas (hydrogen in this case) is eventually required, because the contribution of various relaxation phenomena is not known to the degree of accuracy needed for some applications.

The basic principle of measuring is the propagation of an ultrasonic pulse from one piezoelectric transducer to another piezoelectric receiver across the gas whose temperature is to be measured. A timing unit provides the trigger signal that initiates the sonic pulse, the received pulse produces another signal, and the time difference between the two signals is measured. The sonic probe elements, which may require some cooling, should be constructed so that high temperature, high pressure, and high radiation (especially in this case), would not affect the total operating time. The acoustic properties of such transducer materials as quartz, for example, would not be altered more than 5% by the experiment. Measurements, by the Parametrics group, were made more difficult because of the presence of extremely high nuclear fluxes, which could affect their accuracy. Other piezoelectric materials of higher activity are satisfactory, however, provided neutron flexes are one-tenth of those values assumed for this experiment. A particular advantage of this method is that the transducer of the measuring device must be in equilibrium with the gas being measured, since, in effect, the gas itself does the measuring. Because of this arrangement, a gas can be measured as soon as the equipment is set up. Any other direct-temperature transducer must reach temperature equilibrium after immersion in the gas. In addition, this method makes it possible to measure the average gas temperature by measuring the average transit time through the turbulent gas.

The authors of this document (ref. 166) were greatly concerned with the neutron flux creating a severe environment, although other environments are usually of greater interest. Apparently the measured temperature produces an acoustic level of about 175 dB. Also, the transducers must be placed as close as possible to the gas stream without actually affecting the stream.

Because extensive acoustic measurements of rockets were limited to audible sound, the presence of noise at megacycle frequencies, important to ultrasonic measurements, has not been noted. However, work on the spectrum and origins of rocket noise shows that noise of higher frequency is concentrated near the point where the jet emerges from its throat. Therefore, the potentially troublesome megacycle noise in this measurement is located very close to the rocket throat itself, and will not affect any measurements that are reasonably far down the line.

Another analytic acoustic detecting method involves pump discharge oscillation. Jackson describes this procedure in reference 167. In a sense, a part of this work is also directly concerned with acoustic propagation in liquids. The report contains data on the generation of acoustic waves by the flow leaving the impeller of a pump. Of primary interest is the effect of unsteady pressure distribution of these waves on stationary blades downstream of the impeller. A computer program has been written to permit numerical calculation of the pressures due to acoustic effects. Of more general interest in the report is a study of acoustic wave transmission through various parts of a conventional piping system. The waves, generated by the pump, can progress around elbows, through orifices, and along straight pipes in the hydraulic system supplied by the pump. The report also gives an interim insight into a situation in which a very complex acoustic generation and transmission phenomenon occurs.

ACOUSTIC-DELAY TECHNIQUES

An unusual acoustic technique is described in reference 168. This technique makes possible a nonvolatile, updateable information storage system with serial access to data, without the use of mechanically moving parts; the system has a nondestructive data readout. A strain-sensitive ferromagnetic delay line provides the storage medium. Write-in at any specified address is accomplished by the coincidence of a travelling ultrasonic pulse and a properly timed magnetizing-current pulse applied along the axis at the inside of the delay line. The basic principle can be described in further detail. For instance, assume that the delay line is first completely erased, and that it is driven by an acoustic transducer. The transducer can apply sonic pulses to one end of the line, which then propagate down the line. The delay line is also connected to current sources and, since it is ferromagnetic itself, axial current can magnetize the line. If an acoustic pulse (no current) is travelling down the line and current is suddenly applied, the strain pulse changes the remanence of the line, and hence the magnetizing influence of the current pulse. As a result, a small section of magnetization remains on the line at the position of the strain pulse at the moment the current pulse was applied. To detect such a section, a detector is connected to the terminals that are used to apply the current pulse. When another pulse is sent down the line at the same time the pulse passes the location of the remanent magnetic memory element, the detector senses an output voltage pulse.

A single-line model of this acoustic-delay system has been evaluated at a data rate of 330 kHz and arbitrary data patterns. It showed a practicable signal-to-noise ratio over a temperature range of $-20°$ to $85°$ C. Write-in drive energy requirements were about 1×10^{-6} J per bit. Analyses of representative memory systems based on these results include a 512-word by 12-bit configuration organized for 40-microsec access time. The estimated characteristics, with the exception of memory packaging and access circuits, are: (1) 10^{-2} J to update the entire 6144 bits, and (b) a 2.5-oz, 2-cu in. basic memory element.

A variety of line media have been tested including one basic construction in which ultra-thin ferromagnetic layers were produced over a nonmagnetic core by a milling process and another construction involving the deposition of thin magnetic films on various substrate materials. The thinner surface layers produced a faster switching speed, but the substrate characteristics required a major compromise between the lower attenuation of fused silica and the better-matching thermal coefficient of expansion provided by other materials. An attempt was made to use a thinner inside medium, but it was difficult to couple such fine media to the transducer without excessive mechanical impedance mismatch.

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