cursions produced by an end-burning configuration and caused by rapid changes in exhaust area. The specific application of the experimentally derived parameters to other configurations must be tested.

Conclusions

The experimental results show that solid propellants can be thrust modulated over a wide range, and extinction of combustion can occur at the limiting conditions of pressure decay. The pressure excursions during thrust modulations are amenable to analytical treatment. The characterization of repetitive pressure decay and subsequent rise by the combined analytical and experimental methods provdies valuable insight in designing a solid propellant rocket motor capable of thrust modulation.

Atmospheric Acoustics as a Factor in Saturn Static Testing

RICHARD N. TEDRICK*
NASA George C. Marshall Space Flight Center, Huntsville, Ala.

ONE facet of the static test firing of large space vehicles has been the generation of large amounts of acoustic energy. The rapid increase in the size of these boosters during the last few years and the resultant increase in the noise levels generated during their static testing has made the prediction and control of sound generation an important phase of rocketry. This has been true especially since the advent of the Saturn vehicles, which are not only the world's largest tools for extraterrestial investigation but are also the most powerful manmade, steady-state noise generators. Results from field surveys of the noise show that the acoustic power radiated amounts to about $\frac{1}{2}$ of 1% of the total mechanical power of the engines. In the case of the Saturn S-I, this means about 40 Mw. Because of the meteorological factors at the time of firing, this acoustical energy has sometimes been concentrated into relatively small zones in business or residential areas. Such occurrences have heightened the interest in determining what may be the acoustic consequences of static firing even larger rocket vehicles.

Generally, it may be said that the larger the space vehicle that is being tested, the larger is the amount of sound which is radiated into the atmosphere. However, there are two additional factors that greatly affect the response that may be anticipated from the surrounding communities. One of these is the frequency content of the sound from the engine test. It has been shown[1] that, as the thrust of the rocket engine goes up, the peak frequency goes down. This affects the sound level at long ranges because the lower frequencies (below 100 cps) do not attenuate as rapidly. Thus, a larger percentage of the original sonic energy is left to disturb outlying areas. Also, as the peak drops in frequency, additional energy is put into the subaudible range. Since it is these lower frequencies that rattle windows and shake buildings, the "alarm level" is expected to rise with larger boosters.

Another factor affecting the amount of acoustic energy which reaches the surrounding areas is what is known as the "directivity" of the source. This is simply an index of the relative amounts of energy which are directed by the source itself in each direction. Contributing to this are not only the rocket engine and exhaust velocity parameters but also the shape and configuration of the flame deflector and test tower. After the sound has been radiated into the atmosphere, several things can happen: 1) the sound can be propagated normally, as in a still room or large stadium where the effects of wind and temperature are negligible (as on a very still and quiet morning); 2) it can be directed into the upper atmosphere to be dissipated; and 3) it can be directed toward one or more locations on the earth's surface.

To avoid the acoustic problems inherent in the static testing of large space vehicles, a program of "selective firings" has been instituted at Marshall Space Flight Center (MSFC). Methods for forecasting and evaluating the undesirable firing conditions and for locating the areas that may be adversely affected by returning sound have been developed. These have been based upon acoustic and atmospheric soundings for the 36-hr period immediately preceding such a test. This program not only protects the surrounding communities but also allows maximum scheduling flexibility to the test engineer.

Description of the Problem

The Saturn S-I radiates its 40 Mw of power into an atmospheric hemisphere with a very broad directivity[2] and continues over an operational period of approximately 2 min. Since much of its energy is well below 100 cps, the resonances of local structures are sometimes reached.

Under certain unfavorable atmospheric conditions, those sound rays emanating from the source at angles with the horizontal up to 20° or more can be refracted such that they return to the earth's surface at considerable distances and focus a seriously high acoustic intensity within a relatively small area. Thus, on occasion, propagated sound from the Saturn test has produced annoyance and alarm at ranges of 10 miles or more within the city and suburbs of Huntsville.

Actual sound fields that exist in typical out-of-doors situations are almost prohibitively difficult to describe in detail. Since the medium for acoustic transmission is the atmosphere, it is never either homogeneous or quiescent and the boundary conditions are often quite complicated in terms of contour, vegetative covering, and manmade structures. However, it is possible to treat the problems in an approximate way by considering the following principal elements of sound propagation theory: 1) attenuation by spherical divergence, or the spreading out of the wave front; 2) attenuation due to the mechanical properties of the molecular structure of the atmosphere; 3) attenuation due to ground effects along the earth's surface; and 4) attenuation by refraction of sound fronts resulting from spatial variations in air temperature and wind. The most important of the foregoing elements, in terms of the Saturn noise problem, is the refraction effect, which is responsible not only for bending the sound rays back to the earth but often results in focal areas of concentrated sound energy.[3]

Calculation of Refractive Effect

Since the sound velocity in air depends upon temperature, humidity, and wind, it is the variation of these factors with altitude which determines the verticle sound velocity gradient and ultimately the refraction of sound waves. Considering first the effects of temperature and humidity, the sound speed C in still, dry air is given by LaPlace's equation

$$C = K\,(T^*)^{1/2} \tag{1}$$

where K is a constant (20.07 for C in meters per second) and T^* is in degrees Kelvin. The virtual temperature is T^*, which is defined as that temperature for the density of a parcel of dry air to equal that of moist air under the same pressure. Virtual temperature is related to the actual temperature T by the following expression:

$$T^* = T/[1 - 0.377\,(e/p)] \tag{2}$$

where e is the water vapor pressure and p the total pressure.

Presented as Preprint 64-207 at the 1st AIAA Annual Meeting, Washington, D. C., June 29–July 2, 1964; revision received August 17, 1964.

* Acoustic Physicist, Test Laboratory. Member AIAA.

The sound velocity at a fixed point in terrestrial space is a vector quantity made up of two components: 1) a vector whose magnitude is given by C and whose direction is normal to the wave front at the point and 2) the vector wind at the point. The vertical component of the wind velocity is neglected since instrumentation with which to measure it is not readily available. Furthermore, horizontal gradients of temperature and wind are usually assumed to be negligible over the area affected by the sound source.

Conventional analysis of sound refraction depends upon the concept of sound rays, which are defined as the path of an incremental portion of an acoustic wave front. The direction of the sound velocity is tangent to the ray at each point along the ray. The main transport of sound energy takes place along these rays, and the divergence or convergence of rays indicates decreasing or increasing energy concentration.

Following Cox,[4] the refraction equation for sound rays states that for rays inclined but slightly to the wind

$$C + W_i \cos\theta = A_i \cos\theta \tag{3}$$

where θ is the inclination of sound ray from the horizontal; W_i the component of wind velocity in a given direction; and A_i, constant for any specific sound ray, is the velocity of the intersection of the wave front with the horizontal. Since the wind velocity seldom exceeds 10% of the sound speed within the first 3 to 4 km alt, the refraction equation may be approximated by introducing a new term V_i, defined by $V_i = C + W_i$, so that

$$V_i = A_i \cos\theta \tag{4}$$

Toward any chosen azimuth from the sound source, the elevation angle of the sound ray, at altitude h, is related to the starting evaluation of the ray θ_0 according to the formula

$$V_h \sec\theta_h = V_0 \sec\theta_0 \tag{5}$$

When the sound velocity decreases with height, the ray angle increases and the sound paths may be represented by a secant function. If the sound paths can be regarded as arcs of circles, all of them have the same curvature $[(dV/V)\ dh]$ over altitude intervals where the velocity gradient is constant with altitude. When the value of sound velocity at the earth's surface exceeds all values at higher altitudes, no surface sound return will occur. For a ray to be refracted to the surface from any upper layer, the maximum velocity attained in that layer must exceed the velocity at all points in the medium nearer the surface of the ground.

Attenuation of Sound Along Its Path

Since it is impossible to record the sound at its source because of the extreme conditions within the jet exhaust, it is necessary to evaluate the acoustic source parameters at a reference point several hundred feet away. If the attenuation by spherical divergence is considered, the loss in decibels of the sound level at point P (at a distance R from the source) relative to that at a reference point P_0 (at a distance R_0) from consequence of the inverse first power law is

$$P = A/R \tag{6}$$

where P is the sound pressure amplitude and A is a constant. In the absence of other effects, such as refractive focusing of sound energy, the sound level will decrease by 20 db for each tenfold increase in R from a chosen reference point. Expressed another way, there is a loss of 6 db each time the range doubles.

The attenuation due to atmospheric absorption is comprised of: 1) "classical" absorption, produced by viscosity, conduction, diffusion, and radiation effects; 2) molecular absorption, which strongly depends upon the humidity; and 3) eddy attenuation, due to turbulent fluctuations in the wind structure. The effects of classical absorption are negligible, and at the lower audible frequencies that are of concern in this study, the molecular absorption (which depends upon the second power of the sound frequency) is quite weak. Under typical atmospheric conditions, the sound loss due to molecular absorption is approximately 0.5 db/km at 30 cps and four times as high at 300 cps.

The ground attenuation can be estimated from a knowledge of the acoustic properties of the surface boundary layer, in addition to the sound frequency, the heights of the source and receiver, and the horizontal components of the source-receiver distance. For the special case in which the source and receiver are both very near the ground (the ground is absorbant) and the distance is sufficiently great, the sound pressure is proportional to the inverse square of the distance.[5] When the ground absorption coefficient nears unity, the sound loss due to ground attenuation approaches that resulting from spherical divergence.

General Approaches to the Problem

The Test Laboratory of MSFC found it necessary to consider the effects of long range acoustic propagation since, during certain Saturn static tests, focusing and/or intensification of sound generated during the tests did occur.

To improve public relations with the neighboring communities, the Test Laboratory has initiated a policy of "selective firing," i.e., avoiding the testing of the Saturn under atmospheric conditions conducive to high sound pressure levels in the Huntsville area. The first indication of the existence of such conditions may be taken from an appraisal of the acoustic profile (the velocity of sound vs altitude curve) along the azimuths of interest.

Another method for predicting the sound pressure levels that will result from a Saturn static test relies upon the use of a high-powered sound source that can be used to approximate the noise from the space vehicle test.[6] A random siren coupled to an exponential horn is sounded every half hour. The change in time in the sound pressure levels from this siren is compared to those predicted by the forecaster.

Thus, the problem has been attacked in two ways: 1) routine measurements of the wind, temperature, and humidity variations with altitude and 2) the calculation of the resulting acoustic velocity profiles and direct measurement of the far-field acoustic propagation characteristics of the atmosphere. As test time approaches, the acoustician and the test engineer have several independent evaluations of what may be the acoustic ramifications of such a test. This system provides the test engineer the most flexibility in his test scheduling and still allows him to protect the surrounding communities.

Conclusions

Until recently, few persons in the fields of rocketry and space exploration were concerned with rocket-testing noise. However, the rapid increase in the size of the vehicles to be tested has led to large numbers of claims for damage and annoyance on some projects. The accelerated programs that have been carried on at MSFC in the development of the large siren systems, full-scale sound suppressors and atmospheric acoustic propagation studies point the way by which the rocket industry can avoid costly modification to the vehicles themselves or the purchase of a great deal of expensive real estate.

Much work remains to be accomplished; it is expected to proceed concurrently with booster development. In the field of atmospheric propagation, MSFC has under construction a line of acoustic monitoring stations beginning at the S-IC static test tower and running through the city of Huntsville, Alabama. This array will allow a more complete investigation of the role of weather in the focusing of sound.

References

[1] Tedrick, R. N., "Calculation of the far-field acoustic effects of static testing of large space vehicles," Marshall Space Flight Center Rept. MTP-Test-63-3 (February 1963).

[2] Dorland, W. D., "Far-field noise characteristics of Saturn static tests," NASA TN-D-611 (August 1961).

[3] Tedrick, R. N. and Peterson, R. E., "Studies in far-field acoustic propagation," NASA TN-D-1277 (August 1962).

[4] Cox, E. F., Plagge, H. J., and Reed, J. W., "Meteorology directs where blast will strike," Bull. Am. Meteorol. Soc. **35**, 95–103 (1954).

[5] Nyborg, W. L. and Mintzer, D., "Review of sound propagation in the lower atmosphere," Wright Air Development Center TR 53-354 (1957).

[6] Tedrick, R. N., "Performance characteristics of a large free-field exponential horn," Marshall Space Flight Center Rept. MTP-Test-63-4-(1963).

One-Arc-Second Simulator for Orbiting Astronomical Observatory

B. T. Bachofer* and L. T. Seaman†
General Electric Company, Valley Forge, Pa.

THE air-bearing platform has been in use less than five years in the development testing of new stabilization and control systems for spacecraft, during which time it has proved its value for qualitative evaluation of new system concepts. However, as the precision of new systems increased and the control torque level decreased, use of the air-bearing platform has encountered problems, chief of which is the difficulty of keeping platform disturbance torques low (a few thousand dyne-centimeters) in comparison with the available control torque. Another problem is the need to measure, both independently and accurately, the angular position of the platform. For the improved control systems now being developed, the desired precision is better than 1 arc-sec. This problem is further complicated by the need for accurate determination of the location of the celestial references (i.e., sun and stars) used by the control system under test. Solutions to these problems have been found and implemented during recent air-bearing tests of the stabilization and control system for NASA's Orbiting Astronomical Observatory (OAO). Results of these tests conducted at General Electric were excellent, demonstrating the required 1-arc-min accuracy of the coarse pointing star stabilization loop and 1-arc-sec accuracy of the fine pointing loop.

The control system orients the OAO telescope to any direction in the universe on command from the ground. It does this accurately and reliably for a mission life of one year. A typical flight profile of the OAO control system will follow this sequence.

Initial Stabilization

Starting shortly after separation from the booster, the spacecraft will rotate so that the rear of the vehicle points to the sun. The sun control loop is used. Coarse sun sensors provide error signals, and high-torque nitrogen reaction jets generate torques for this phase of operation. Once the sunline is achieved, the system switches to fine sun sensors (for added precision) and to flywheel control. Accuracy is 15 arc-min.

Roll Search

Immediately after fine sun stabilization is achieved, the spacecraft is rolled about the sunline at a constant low rate. Roll control is achieved with the rate stabilization loop consisting of rate gyros and reaction jets. Each of the six star trackers is commanded to point to the expected direction of a preselected guide star during this period.

Star Acquisition

When two, three, or four preselected guide stars are simultaneously detected by the appropriate star trackers, the desired stellar reference system is assumed to have been attained, and the roll search is stopped with a reverse jet. At this instant, each tracker is allowed to track its guide star and the entire system is switched to sun-sensor/rate-gyro control to star-tracker control. The system thereafter stabilizes under flywheel torque to the commanded stellar reference.

Reorientation

The spacecraft is quickly maneuvered to a new orientation relative to a stellar reference by commanding a set of coarse flywheels to rotate, each in turn, a given number of revolutions and then to brake to a complete stop. This is the slew control loop. Although the star control loop is inoperative during this maneuver, the star trackers remain locked on their guide stars, and a new command angle is introduced for each tracker gimbal. Once reorientation is complete, star control is re-established and the vehicle settles to a new vehicle orientation relative to the original stellar reference. If a new stellar reference is needed (for maneuvers beyond the tracker gimbal freedom), one or more star trackers is commanded, in turn, to point to and therefore acquire new guide stars. This "leap frog" method of establishing a stellar reference from any 2 or more of the 30 to 40 possible guide stars allows reorientation to any desired spacecraft attitude.

Coarse Pointing

At each spacecraft attitude, the star control loop orients the spacecraft to an absolute accuracy of 1 arc-min with respect to the commanded attitude. Once attained, an attitude must be held to better than 15 arc-sec for a 50-min period. Flywheel unloading (accomplished by a low-torque reaction jet, closed-loop technique) will not occur during this 50-min period at the expected level of orbital disturbance torques.

Fine Pointing

Once within the small field of view of the experimenter's telescope, or if permitted by ground command, the system will automatically switch to control by the fine error sensor of the telescope. The accuracy of this control is 1 arc-sec for the Goddard experiment and 0.1 arc-sec for the Princeton experiment.

Air Bearing Facility for OAO

The facility for testing the OAO Stabilization and Control System was designed for and has been used to perform both developmental and acceptance tests. Wherever possible, tailor-made designs were avoided in order to give the laboratory flexibility; however, the specific OAO requirements served as the minimum performance requirements for the facility. A description of the major equipments follows.

Air bearing platform

The air-bearing platform simulates the dynamic characteristics of the OAO spacecraft on a one-to-one basis. For the purpose of structural rigidity, the platform is ruggedly constructed, weighing 8500 lb, with inertias of 1450 slug-ft^2. This compares with 3600 lb for the spacecraft with the same inertias. The roll axis (the optical axis of the main experiment) of the air-bearing table is vertical and pitch and yaw axes horizontal. The design allows $\pm 30°$ freedom of movement about the pitch and yaw axes and unlimited freedom about the roll axis. The platform uses a 10-in. stainless-steel bearing with a multiorifice, floating seat design.

Presented as Preprint 64-205 at the 1st AIAA Annual Meeting, Washington, D. C., June 29–July 2, 1964; revision received November 30, 1964.

* Manager, OAO Systems Evaluation Engineering, Missile and Space Division.

† Manager, OAO Engineering, Missile and Space Division.