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RELAXATION AND TURBULENCE EFFECTS ON SONIC BOOM SIGNATURES

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OVERVIEW

The rudimentary theory of sonic booms predicts that the pressure signatures received at the ground begin with an abrupt shock, such that the overpressure is nearly abrupt. This discontinuity actually has some structure, and a finite time is required for the waveform to reach its peak value. This portion of the waveform is here termed the rise phase and it is with this portion that the present presentation is primarily concerned.

Any time characterizing the duration of the rise phase is loosely called the "rise time." Various definitions are used in the literature for this rise time; for the present discussion it can be taken as the time for the waveform to rise from 10% of its peak value to 90% of its peak value. The available data on sonic booms that appears in the open literature[1] suggests that typical values of shock overpressure lie in the range of 30 Pa to 200 Pa, typical values of shock duration lie in the range of 150 ms to 250 ms, and typical values of the rise time lie in the range of 1 ms to 5 ms.

The understanding of the rise phase of sonic booms is important because the perceived loudness of a shock depends primarily on the structure of the rise phase. A longer rise time typically implies a less loud shock. A primary question is just what physical mechanisms are most important for the determination of the detailed structure of the rise phase.

A prevalent viewpoint in current literature on sonic booms is that molecular relaxation is the dominant physical mechanism for establishing the finite rise times of sonic booms. That such should be the case was first proposed by Hodgson[2] in 1973. The other contender for being the dominant mechanism is distortion by atmospheric turbulence, and earlier theories as to how this mechanism affects the rise phase had been proposed by Pierce[3] and by Plotkin and George[4], but without any attention to the effects of molecular relation. A subsequent analysis by Ffowcs-Williams and Howe[5] suggested, however, that turbulence was too weak a mechanism to account for the observed magnitudes of the rise times, and these authors concluded their article with a statement to the effect that molecular relaxation appeared to be sufficient to explain the existing data. Bass and his colleagues[6] carried out some numerical simulations of long range weak shock propagation under the influence of molecular relaxation and confirmed that the general trends observed regarding the ranges of rise time and their dependences on peak overpressures could be more or less well explained in terms of a molecular relaxation mechanism. Tubb[7], and also Bass and other colleagues[8], carried out laboratory-scale experiments on the propagation of weak shocks through turbulence and did not observe that the presence of turbulence caused appreciable increased thickening of weak shocks (i.e., increased rise times).

Although there appears to be no doubt now that the molecular relaxation theory does indeed predict the correct order of magnitude of the rise time, the dismissal of turbulence as a dominant mechanism is not at all justified by the work cited above. The theoretical work of Ffowcs-Williams and Howe cannot be regarded as definitive and has recently been criticised in a review article by Plotkin[9]. The laboratory-scale experiments of Tubb[7] and of Bass *et al.*[8] are also criticised by Plotkin, on the basis that the type of turbulent distortion that affects sonic booms requires long propagation distances and that such cannot be easily be simulated in a laboratory environment.

Notwithstanding the reservations mentioned above concerning atmospheric turbulence, it is possible to begin with the assumption that molecular relaxation is indeed the overwhelmingly dominant mechanism as a working hypothesis and then to test it with a combination of experiment and theory. Until recently, an adequate test of such a hypothesis had not yet been carried out. The numerical predictions of rise times of sonic booms have been based on either relatively crude theories or on unwieldy and somewhat erratic results of lengthy computer runs.

To test the hypothesis that molecular relaxation satisfactorily explains the rise phase portion of sonic boom waveforms, one does not need to explicitly consider turbulence. If the test suggests that the hypothesis is grossly incorrect, then one does not necessarily conclude that turbulence is the correct explanation, but the stage is certainly set for giving turbulence further serious consideration.

For propagation of sonic booms and of other types of acoustic pulses in nonturbulent model atmospheres, there exists a basic overall theoretical model that has evolved as an outgrowth of geometrical acoustics. This theoretical model depicts the sound as propagating within ray tubes in a manner analogous to sound in a wave guide of slowly varying cross-section. The propagation along the ray tube is quasi-one-dimensional, and a wave equation for unidirectional wave propagation is used. A nonlinear term is added to this equation to account for nonlinear steepening and the formulation has been carried through to allow for spatially varying sound speed, ambient density, and ambient wind velocities. The model intrinsically neglects diffraction, so it cannot take into account what has previously been mentioned in the literature as possibly important mechanisms for turbulence-related distortion. The existing ray-tube type model is reviewed by Plotkin[9] and there exist computational codes based on this model. The two rudimentary codes are those of Hayes *et al.*[10] and Thomas.[11] Taylor[12] extended Hayes's model such that the resulting program was applicable for the analysis of booms that proceeded initially obliquely upwards and which were eventually refracted back to the ground by sound speed and wind speed gradients. His modification also yields waveforms that have come along paths that touched caustics. The model as it presently exists can predict an idealized N-waveform which often agrees with data in terms of peak amplitude and overall positive phase duration. It does not take dissipation or relaxation effects explicitly into account, so it does not predict detailed shock structure and rise times. It is possible, however, develop a simple method based on the physics of relaxation processes for incorporating molecular relaxation into the quasi-one-dimensional model of nonlinear propagation along ray tubes.

The theory, developed in recent work by Pierce and Kang[13] and described in detail in the recent doctoral thesis of Kang[14], for the incorporation of molecular relaxation into the overall ray-tube propagation model hypothesizes that molecular relaxation is important only in the rise phase of waveforms. Such is justified because the characteristic times, such as positive phase duration, associated with other portions of the waveform are invariably much longer than the characteristic relaxation times for molecular relaxation. During most of the time at which the waveform is being received, it is reasonable to assume that the air is in complete quasi-static thermodynamic equilibrium. Molecular relaxation is a nonequilibrium thermodynamic phenomenon and is important only when pressure is changing rapidly, with characteristic times of the order of a few milliseconds or less.

A second hypothesis, which is related to the first, but which requires some extensive analysis for its justification, is that the rise phase of the waveform is determined solely by the peak overpressure of the shock and the local properties of the atmosphere. Strictly speaking, one expects the waveform received at a local point to be the result of a gradual evolution that took place over the entire propagation path, so it depends in principle on the totality of the atmospheric properties along the path. However, the N-wave shape, or at least the positive phase portion, is often established fairly close to the source (i.e., the flight trajectory in the case of sonic boom generation) relative to the overall propagation distance. With increasing propagation distance, the peak overpressure decreases, but does so very slowly, and the positive phase duration increases, but also does so very slowly. There is a net loss of energy from the wave and the loss takes place almost entirely within the rise phases of the shocks. However, the manner in which the peak overpressure decreases and the positive phase duration increases is virtually independent of the energy loss mechanism. The rise phase structure of the waveform is basically a tug-of-war between nonlinear steepening and molecular relaxation. When the boom passes through a region where the molecular relaxation is weaker, the nonlinear steepening causes the waveform to sharpen up and causes the rise time to decrease until the mechanisms balance each other out. One can associate some characteristic adjustment time with this restoration of the balance between the two mechanisms. The second hypothesis rests on the assertion that this characteristic adjustment time is substantially less than any characteristic time it takes for the waveform to propagate over a path segment within which the relevant atmospheric properties (especially the absolute humidity) change appreciably.

That this second hypothesis has some credibility can be seen at once when one considers that a upper limit for the relaxation time is about 20 ms (corresponding to the relaxation time of N_2 in very dry air)[15]. The waveform moves with roughly the sound speed, which is of the order of 340 m/s, so a hypothetical relaxation process would take place over a propagation distance of less than 10 m. If the atmospheric humidity does not vary appreciably over such a distance, then one might argue that any relaxation process that was initiated by waveform onset must have taken place at nearly constant atmospheric humidity and that the appropriate value to use is that value that prevails locally. However, this argument is a little simplistic because the characteristic adjustment time is not necessarily the same as the relaxation time. Kang[14] gives an estimate of this adjustment time based on rigorous physical principles and finds that the characteristic adjustment time is of the order of 100 ms, corresponding to a propagation distance of 34 m.

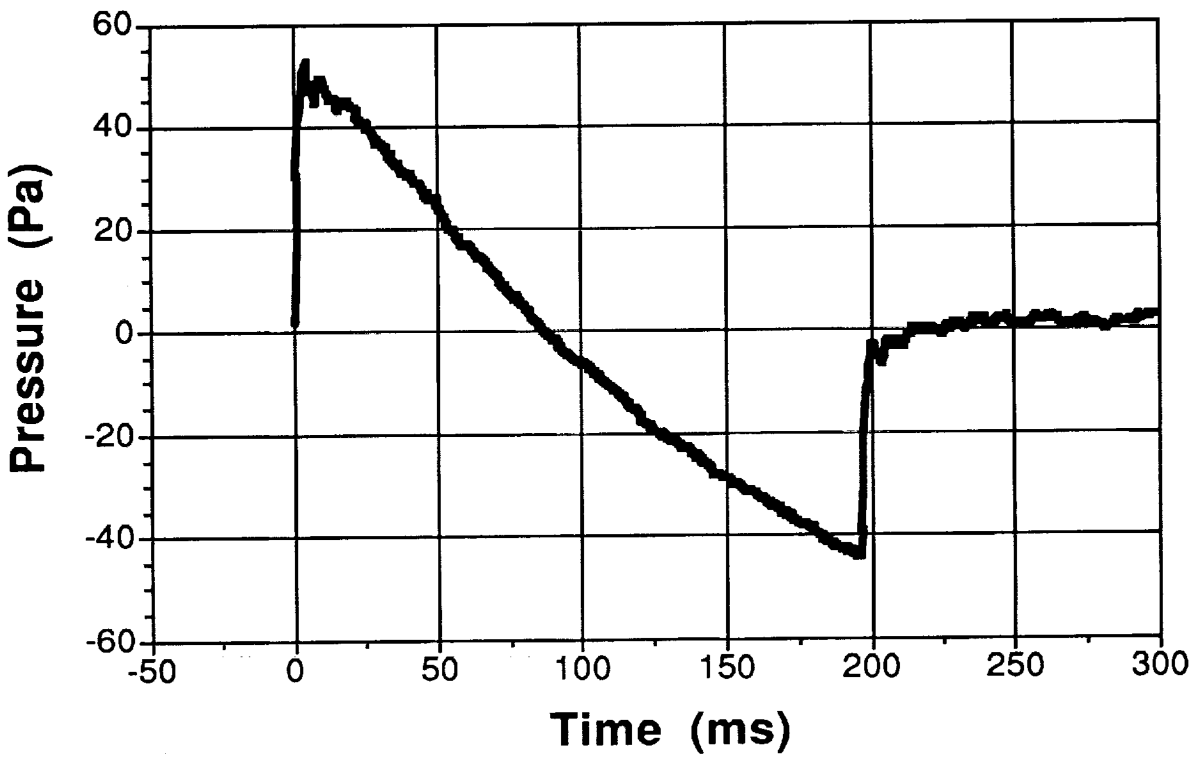
The two hypotheses mentioned above imply that a plane wave propagation model is sufficient to predict the rise phase of the waveform. Another implication is that one can always carry out the calculation in a reference frame where there is no wind, so the model need not consider ambient fluid velocity. This leads one to a relatively simple model of determining a frozen shock profile. The boundary conditions for the calculation of the rise phase then can be reduced to the idealizations that the acoustic portion of the pressure goes to zero far ahead of the shock, and that this pressure asymptotically approaches a constant value P_{sh} far behind the shock.

For the simplified planar model of a step in overpressure propagating through a medium with internal relaxation, a relatively simple set of governing partial differential equations are available. The principal member of this set is here called the augmented Burgers's equation, and it modifies the linear wave equation by including the nonlinear, thermoviscous, and molecular relaxation terms. It was first derived by Pierce[15] in 1981. The remaining equations govern the time dependence of the relaxation of internal variables. These equations are solved by Kang[14] for atmospheric propagation in air consisting of oxygen, nitrogen, and water molecules, using the frozen profile hypothesis. The idea of using such a hypothesis goes back to Taylor[16] and Becker[17], but the application to the augmented Burgers's equation model with two relaxation processes included is relatively recent. Based on the frozen shock profile assumption, the augmented Burgers's equation and relaxation equation are reduced to a set of coupled nonlinear ordinary differential equations, and these can be solved by numerical integration, once appropriate boundary conditions are established.

The predictions of the theoretical model developed in this thesis are compared with actual waveforms of sonic booms, recorded by the US Air Force in the Mojave Desert in 1987, and it is found that molecular relaxation cannot sufficiently explain the finite rise time of sonic booms. In the majority of cases, the rise times of experimental data are larger than predictions by the factor of 2 to 5. A possible explanation for the discrepancy is that atmospheric turbulence may be the dominant mechanism underlying the thickening of weak shocks. Such a supposition is supported by the observations that there is a random scattering in the values of the experimental rise times and that, in a few cases, there is extremely good agreement of the predicted with the experimental waveforms. The data comparison suggests, moreover, that the model based on molecular relaxation provides a lower bound to rise time and an upper bound to loudness.

Sonic Boom - SR-71 Airplane

Mach 2.6, Flight Altitude = 66,000 ft



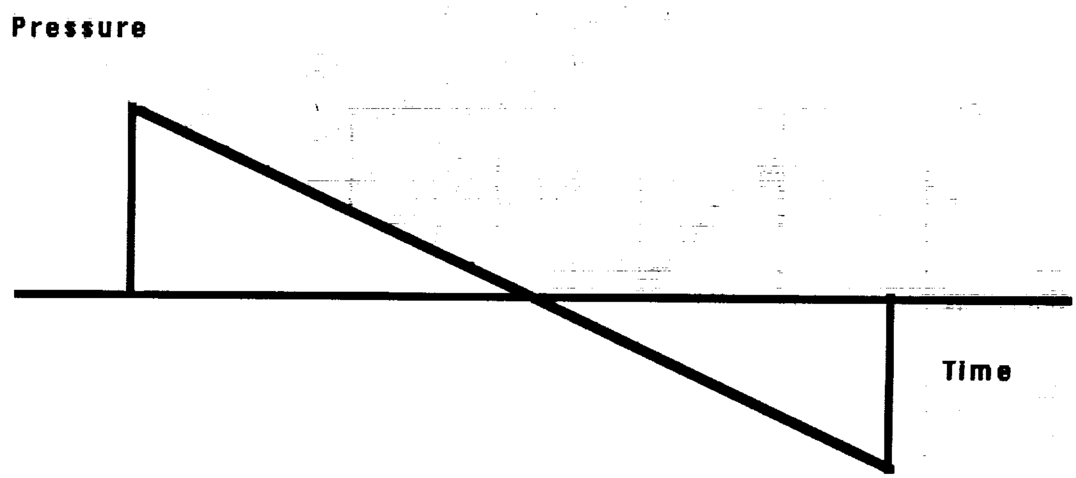
Acoustic Pressure versus Time

recorded on ground directly below

aircraft flight track

Sonic Booms - -

basic result of idealized theory - -

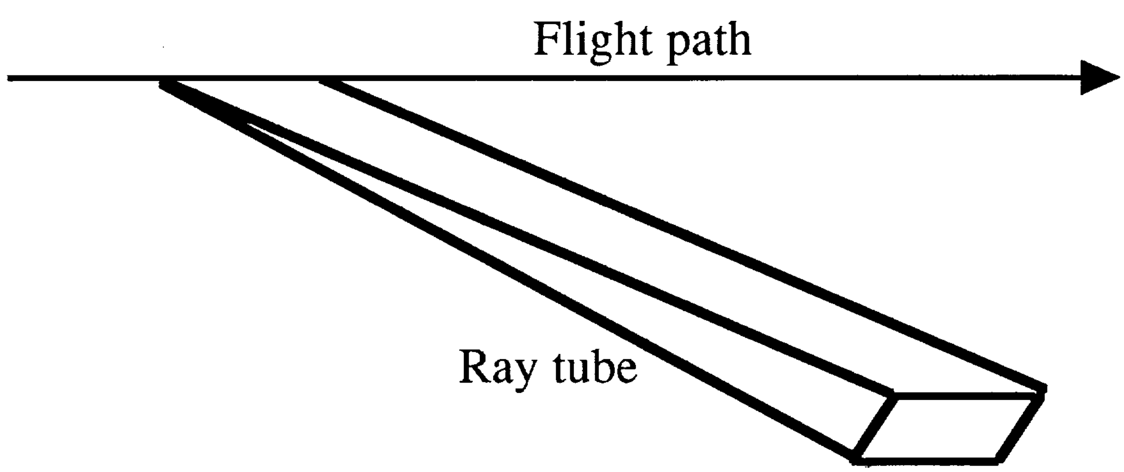


Waveform asymptotically approaches N-wave shape with increasing propagation distance from aircraft

For the Concorde:

Pressure jump approx 100 Pa

Time duration approx 100 ms



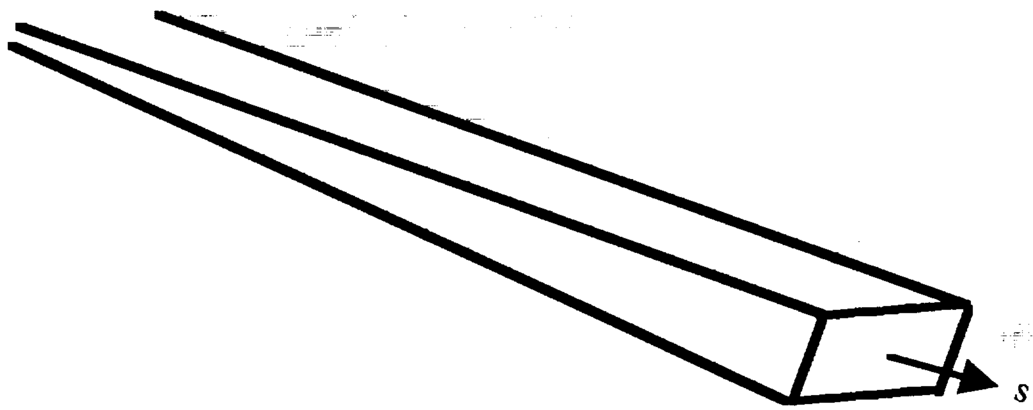
In first approximation:

boom propagates along ray tube

like sound in a waveguide

of slowly varying cross-section

Waveform near flight track is affected by aircraft shape and speed



Waveform near ground is strongly distorted by propagation through the atmosphere.

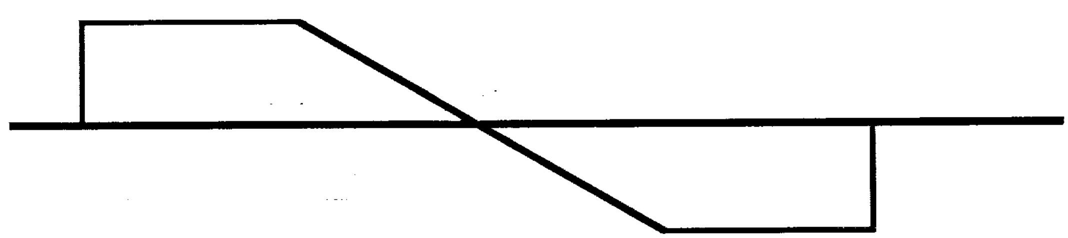
Variations caused by details of aircraft design are washed out.

Sonic Booms - -

prediction of idealized theory - -

waveform at the ground for

possible next generation of SST's

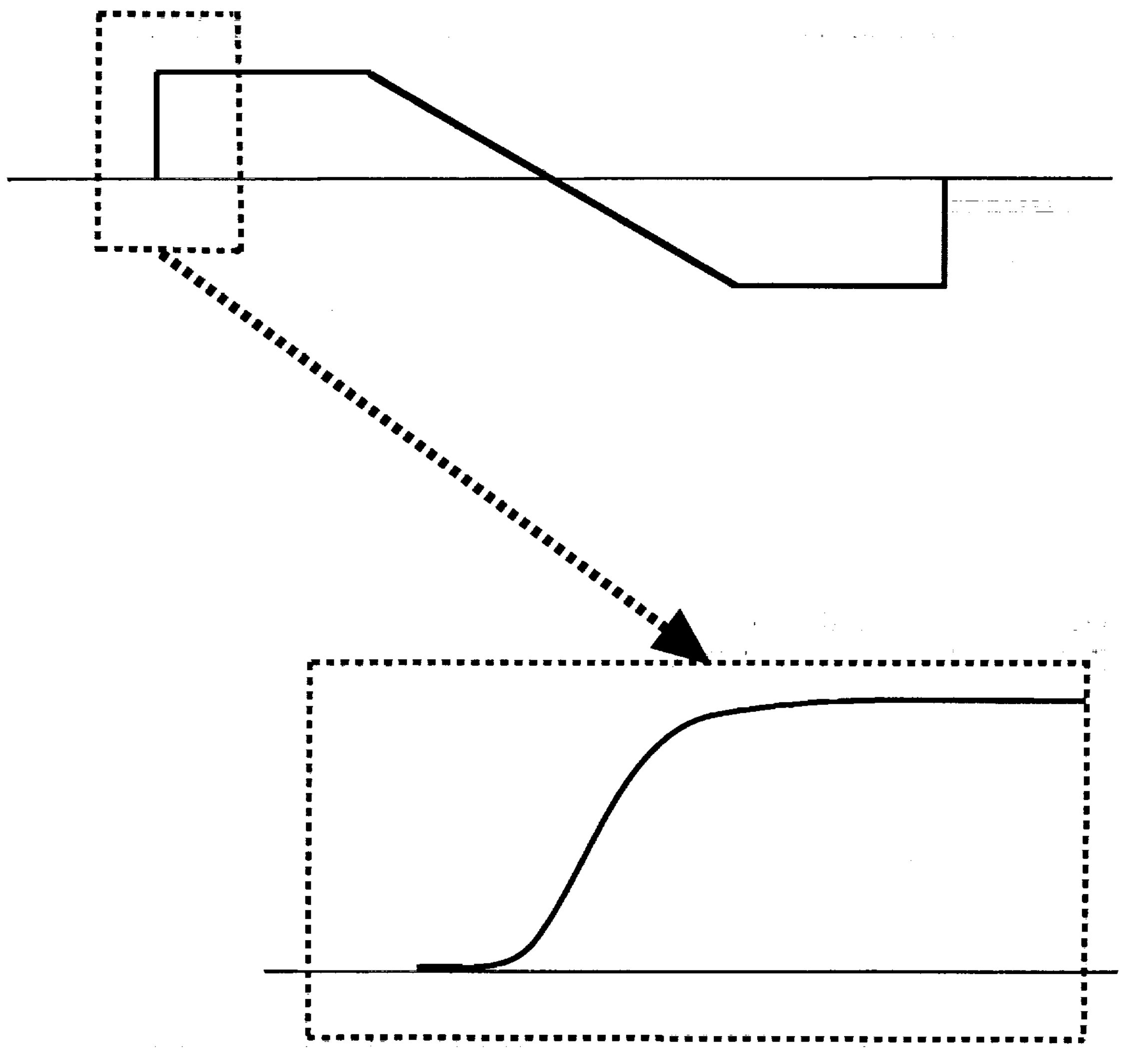


Asymptotic N-wave shape not yet realized - -

Smaller pressure jumps than nominally expected - -

Would this achievement reduce the annoyance?

Actual pressure jumps are not abrupt - -

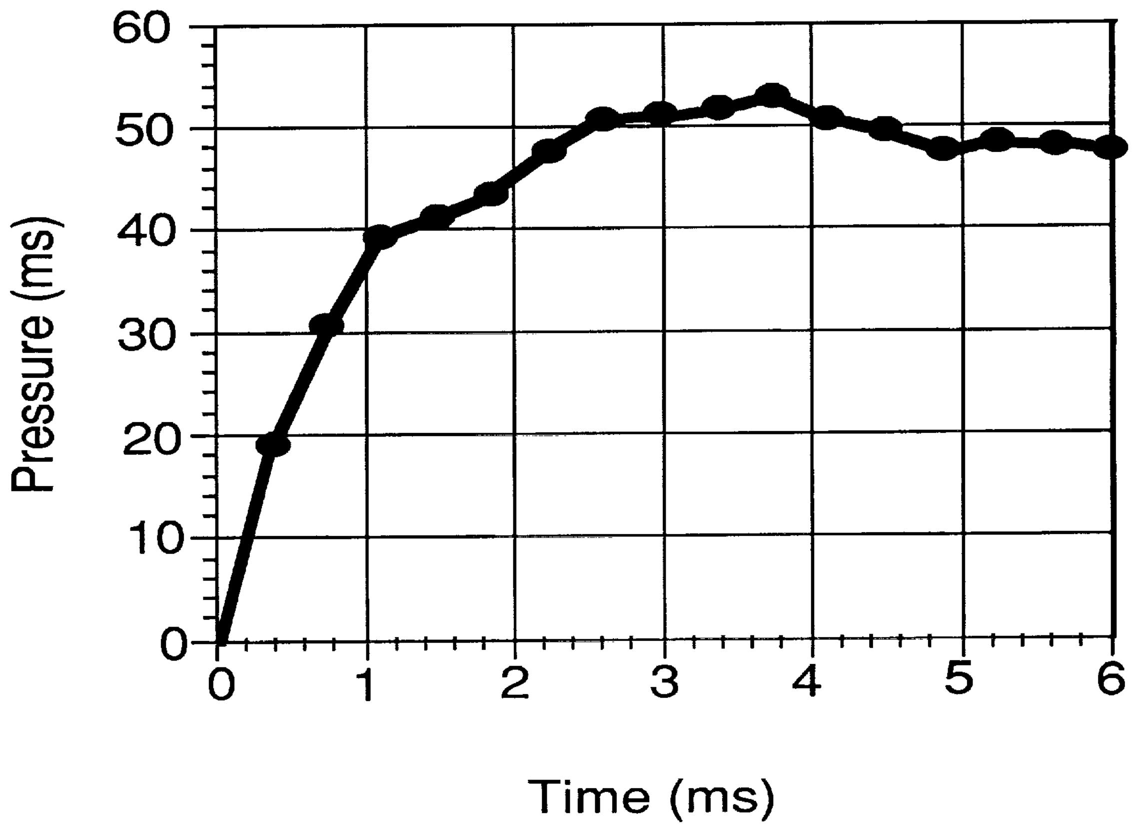


Extent of the absence of abruptness is important - -

the less abrupt the better.

Rise time is a descriptor of absence of abruptness.

Rise phase of a sonic boom - (leading shock in the N-wave)



SR-71 airplane at Mach 2.6; Flight Altitude is 66,000 ft

Flying over the Mojave desert on August 5, 1987, 9:00 a.m.

Hypotheses (to be checked)

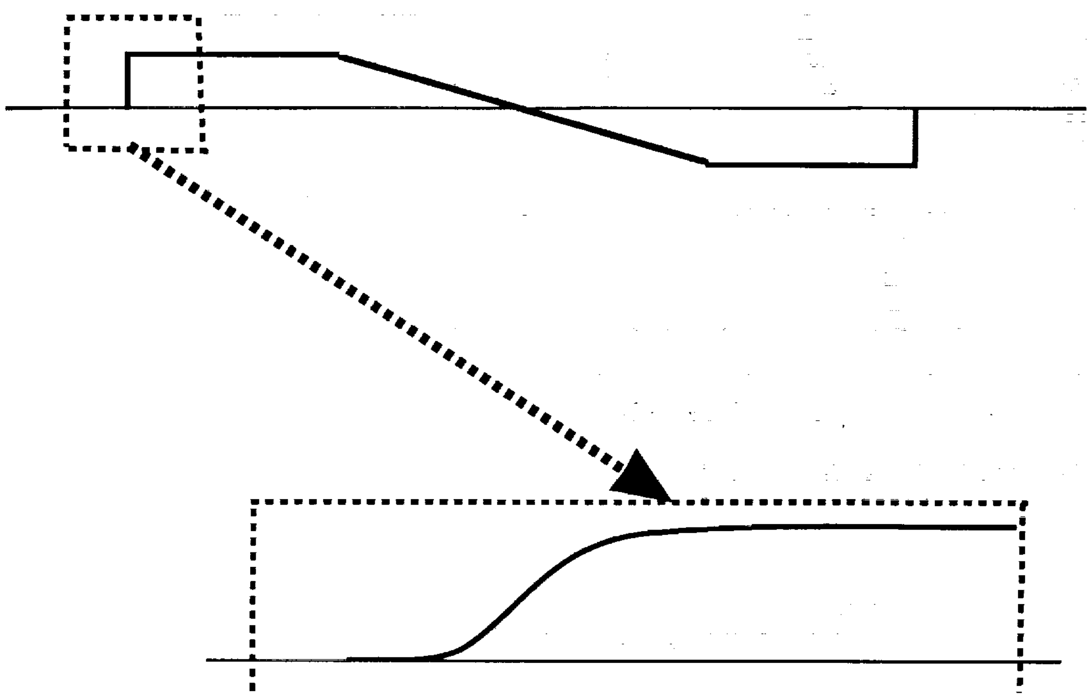
Turbulence usually increases rise-time

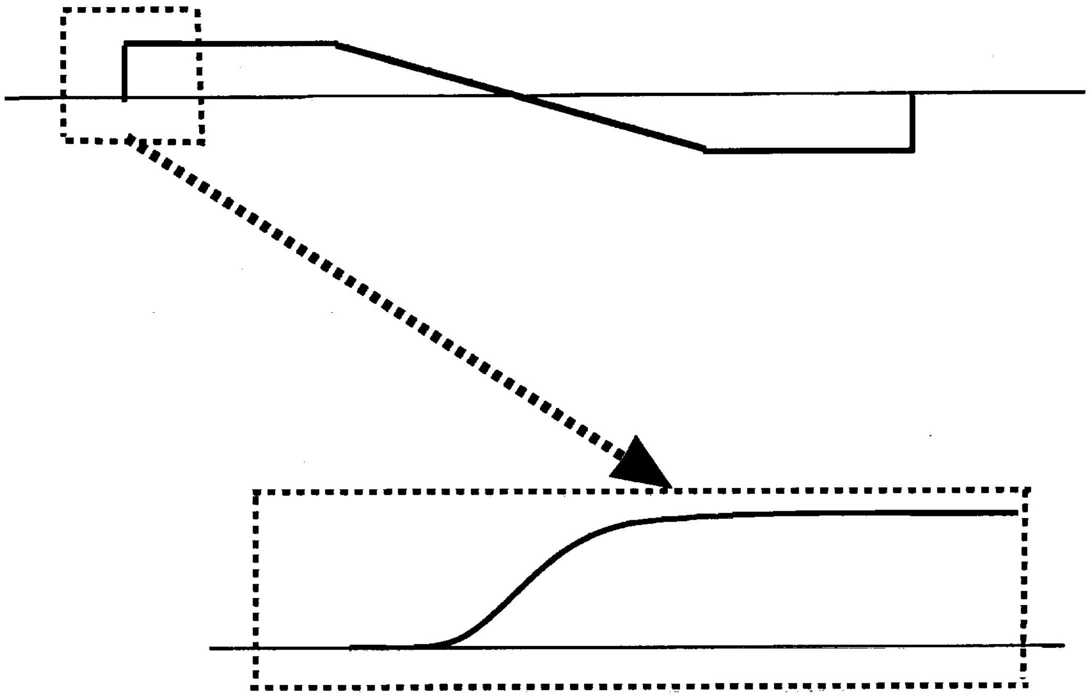
Real gas effects establish minimum expected rise-times

For real gas effects, the profile portion around a shock is independent of

- rest of profile

- evolution along propagation path





(A consequence - for real gas effects)

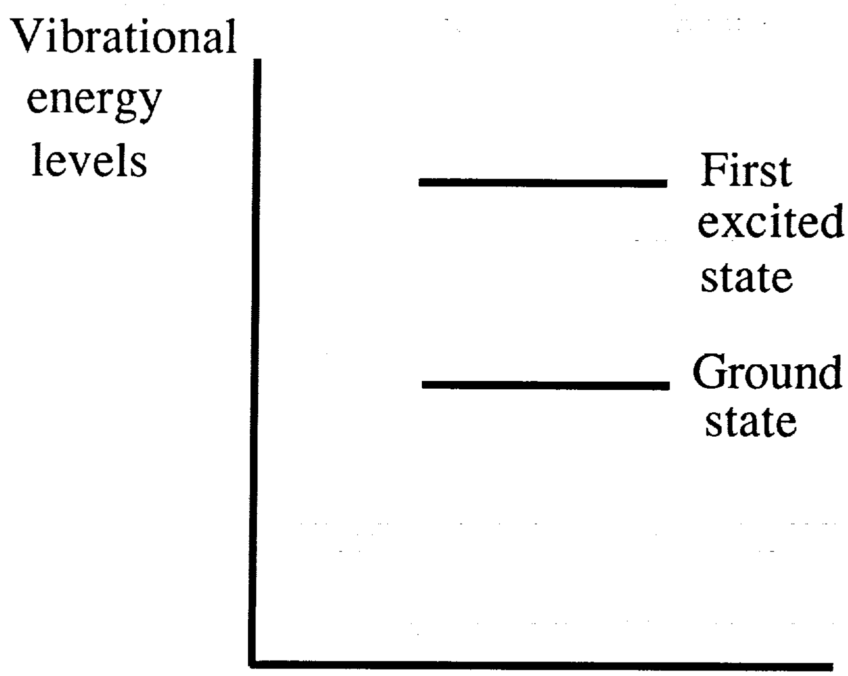
Detailed structure of a sonic-boom waveform near the nominal time of arrival of a shock is determined by only

a. The net pressure jump

b. The local properties of the atmosphere

What is molecular relaxation?

Nitrogen molecule



$$\frac{\text{Number in excited state}}{\text{Number in ground state}} = \text{function of temperatu;e}$$

But this is so only for thermodynamic equilibrium.

Assumptions accompanying molecular relaxation model

- Shocks are weak (typical range: 300Pa max.)
- Molecular relaxation important only in rise phase for oxygen and nitrogen processes
- Rise phase determined solely by peak overpressure of shock and local properties of atmosphere
- Rise phase much shorter in duration than positive phase of the shock

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The shock is modeled as a "frozen profile"

i.e. the shock appears to stand still with respect to ξ

- change of variables: $\xi = x - V_{sh}t$
- V_{sh} = speed of shock propagation.

Molecular relaxation model

Developed by Kang and Pierce, 1990

Uses augmented Burger's equation (Pierce, 1981):

$$\frac{\partial p}{\partial t} + c\frac{\partial p}{\partial x} + NST + TVT + MRT = 0$$

Molecular relaxation term

Thermal viscosity term

Nonlinear steepening term

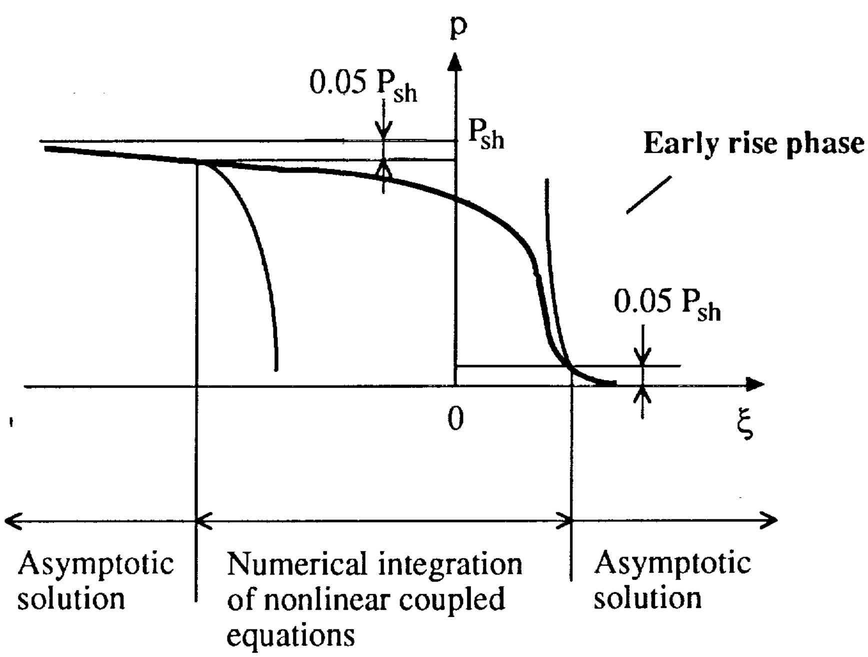
Coupled with Relaxation equation:

$$p_\nu + \tau_\nu \frac{\partial p_\nu}{\partial t} = \tau_\nu \frac{\partial p}{\partial t}$$

$$\nu = O_2, N_2 \text{ process}$$

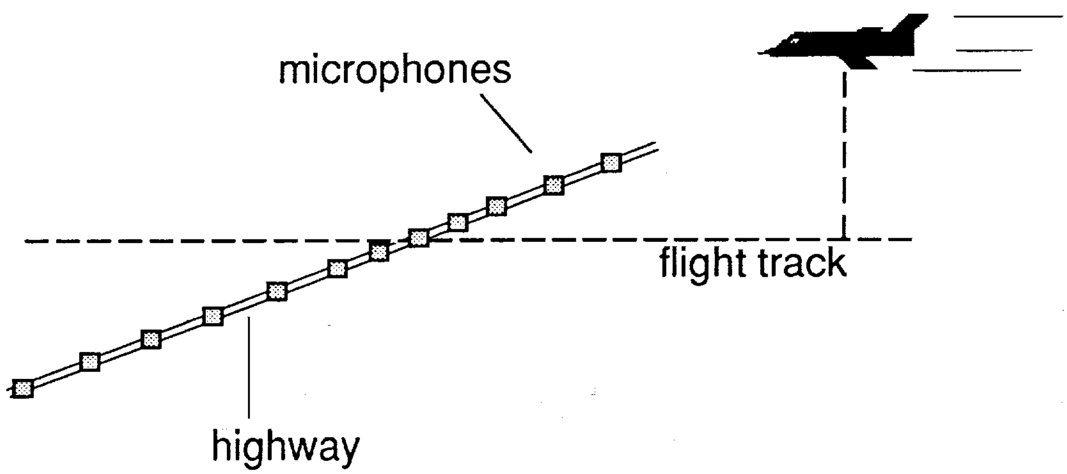
Using the steady-state version of Burger's equation,

The theoretical rise phase is determined using asymptotic and numerical solution methods:



Early rise phase: O_2 relaxation dominates
Later rise phase: N_2 relaxation dominates

Schematic of sonic boom recording setup

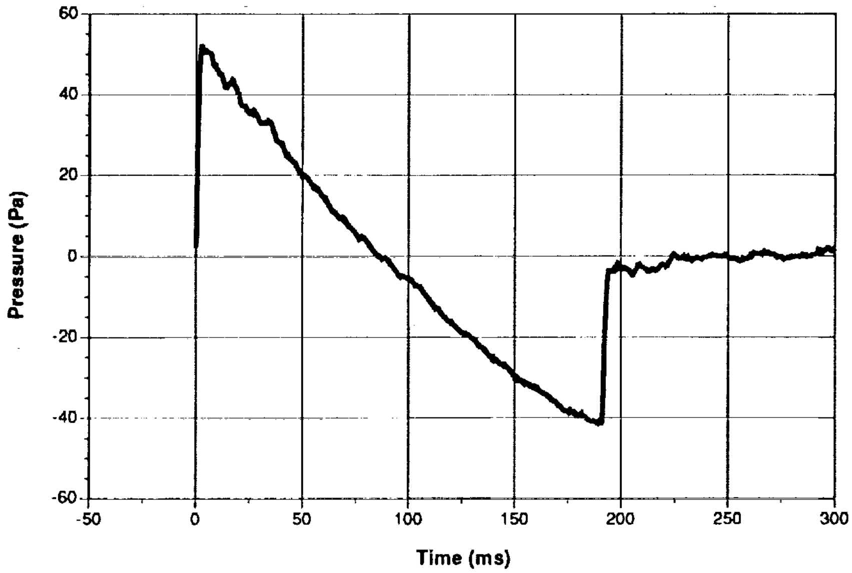


- Microphones in inverted mounts, approximately at ear height

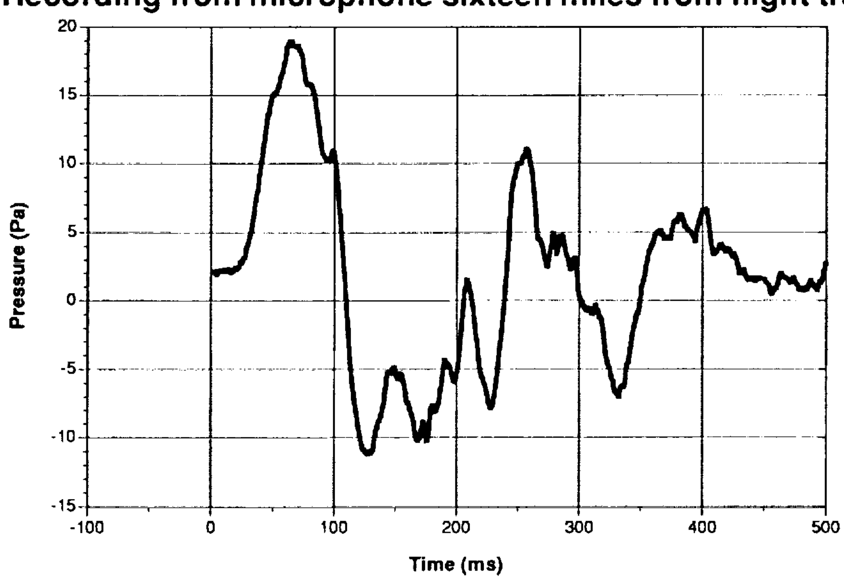
- Flight track perpendicular to highway, and parallel to ground

Pressure vs time recordings of sonic booms:

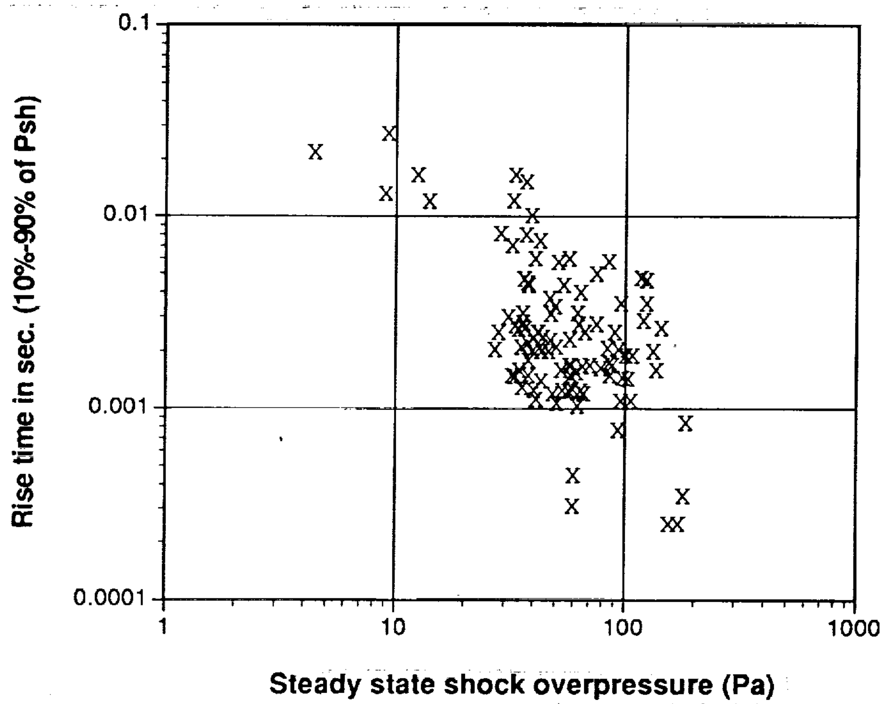
SR-71 aircraft, altitude 66,000 ftMSL
Mach 2.6
Recording from microphone four miles from flight track



F-16 aircraft, altitude 13,100 ftMSL
Mach 1.16
Recording from microphone sixteen miles from flight track

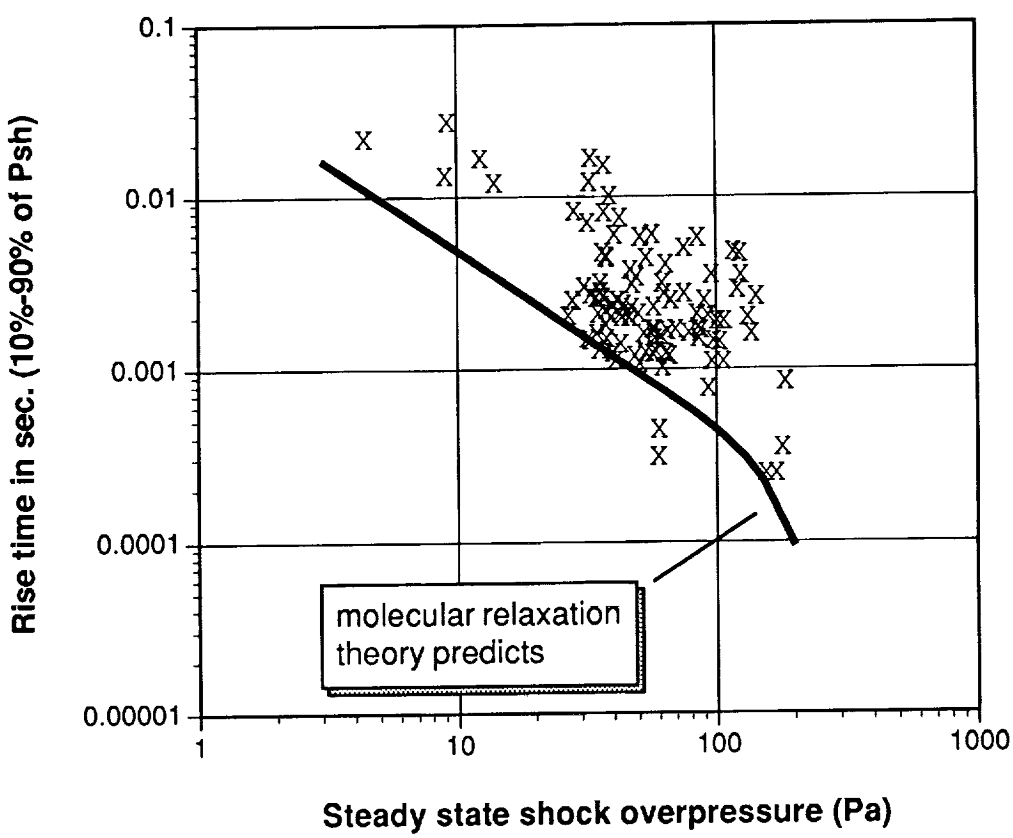


Rise times of recorded sonic booms vs steady state shock overpressure



- Average rise time 2-3ms for steady state shock overpressure range of 30-100Pa
- Rise time inversely proportional to Psh

Rise times of sonic booms vs steady state shock overpressure, as compared to our molecular relaxation model



- At time of experiment: Temp = 30 - 38°C
  Relative humidity = 19 - 26%

- This is a log-log plot

Experiment vs Theory Comparison:

- Experimental rise times are typically two to five times longer than theory would predict.

- Theoretical rise times appear to form a lower bound for experimental rise times.

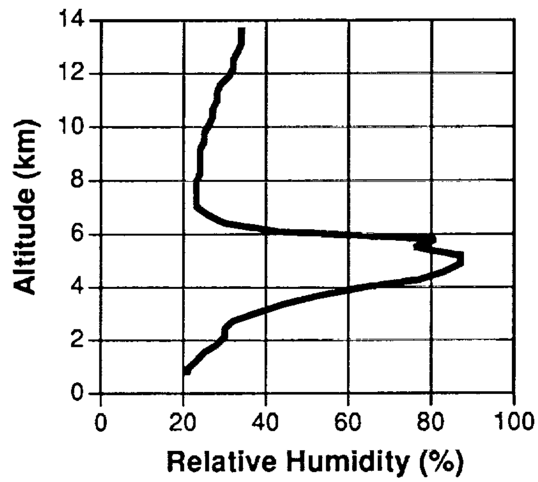
- Approximately 10% of our experimental data agrees well with theory.

- In the majority of cases, molecular relaxation theory does not satisfactorily predict rise time.

Humidity considerations:

- Humidity change affects relaxation theory results

- Weather data: humidity changes with altitude:



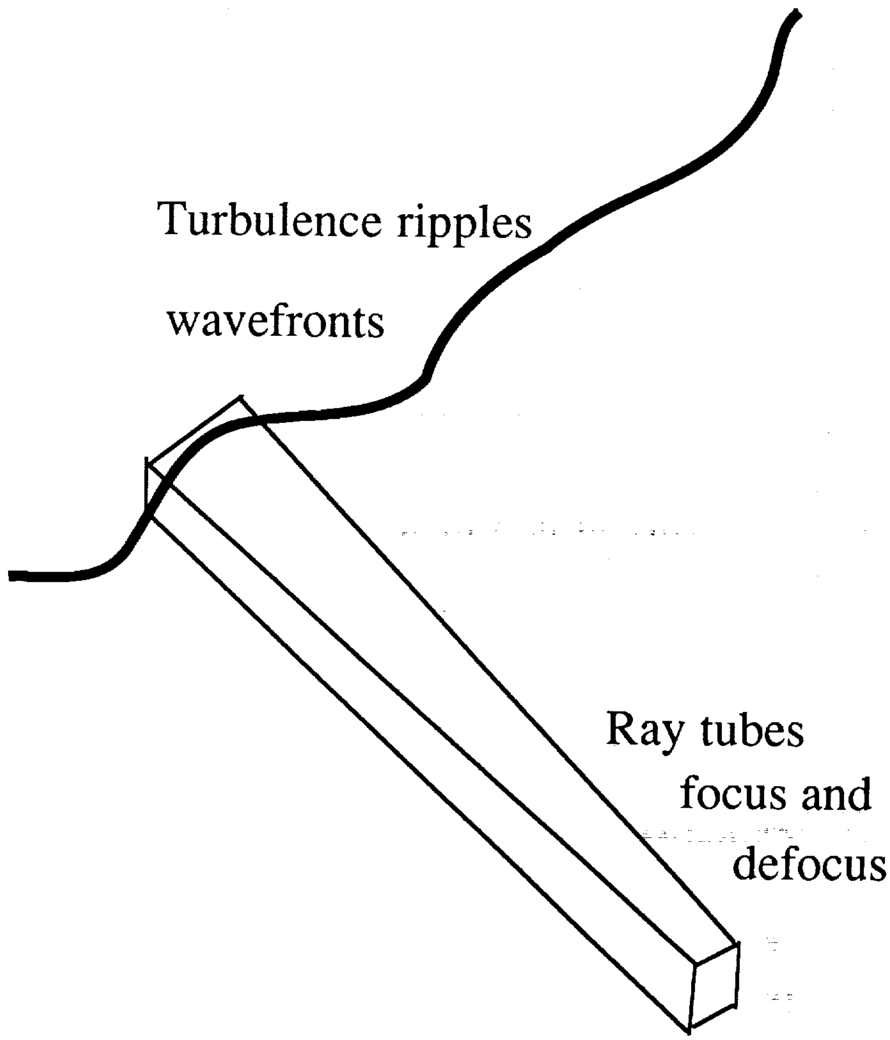
- humidity at its lowest near the ground

- If theoretical rise times calculated for <u>much lower</u> humidity than is actually present, the theory predicts a better match to experimental data

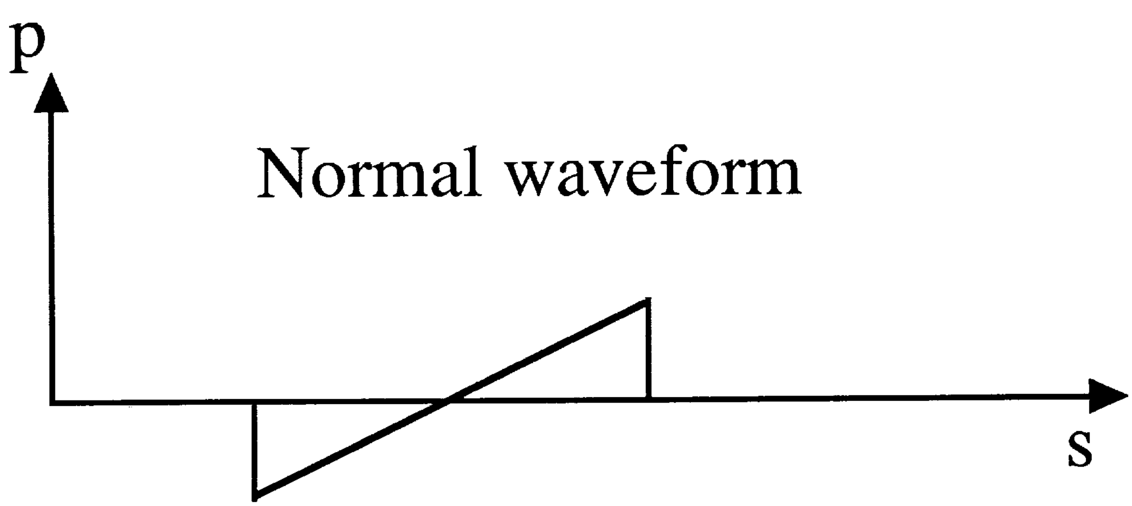
- Considering the higher-humidity regions also, instead of just the humidity at the ground (the current practice), would lead to a worse theoretical prediction.

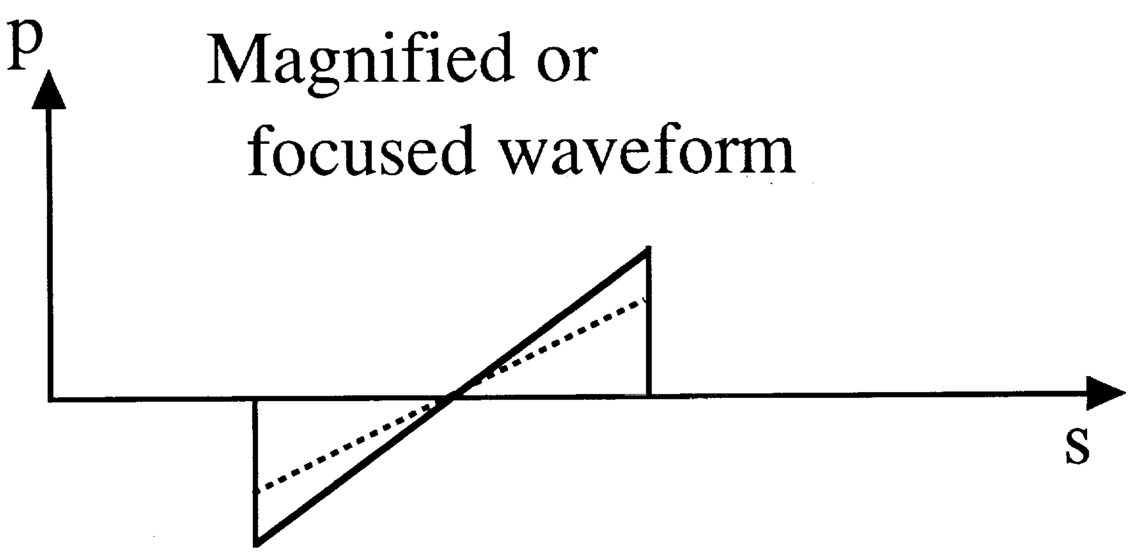
- There is still discrepancy between theory & data

Explanation of spiked and rounded waveforms



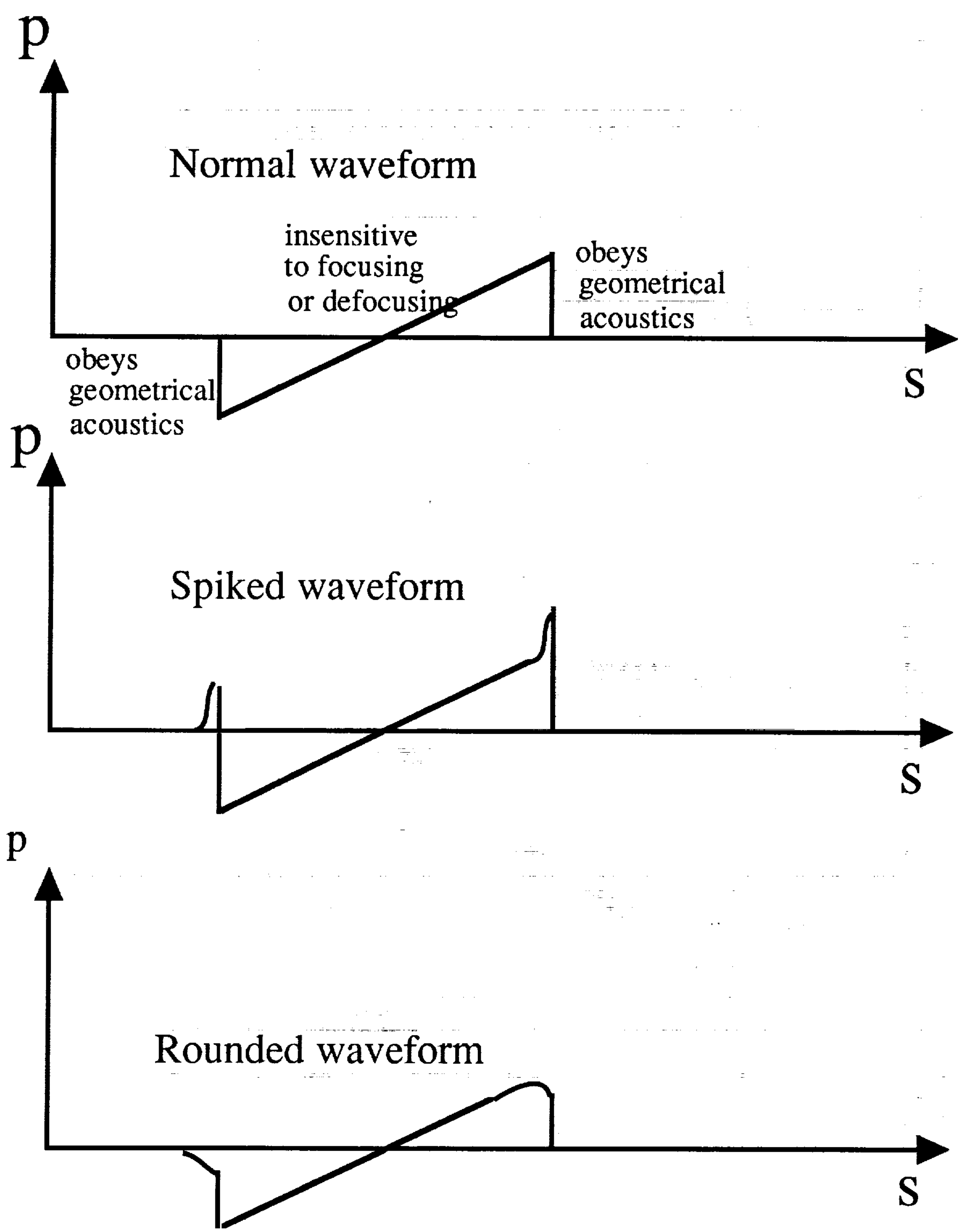
(verified by Davy and Blackstock (1971)





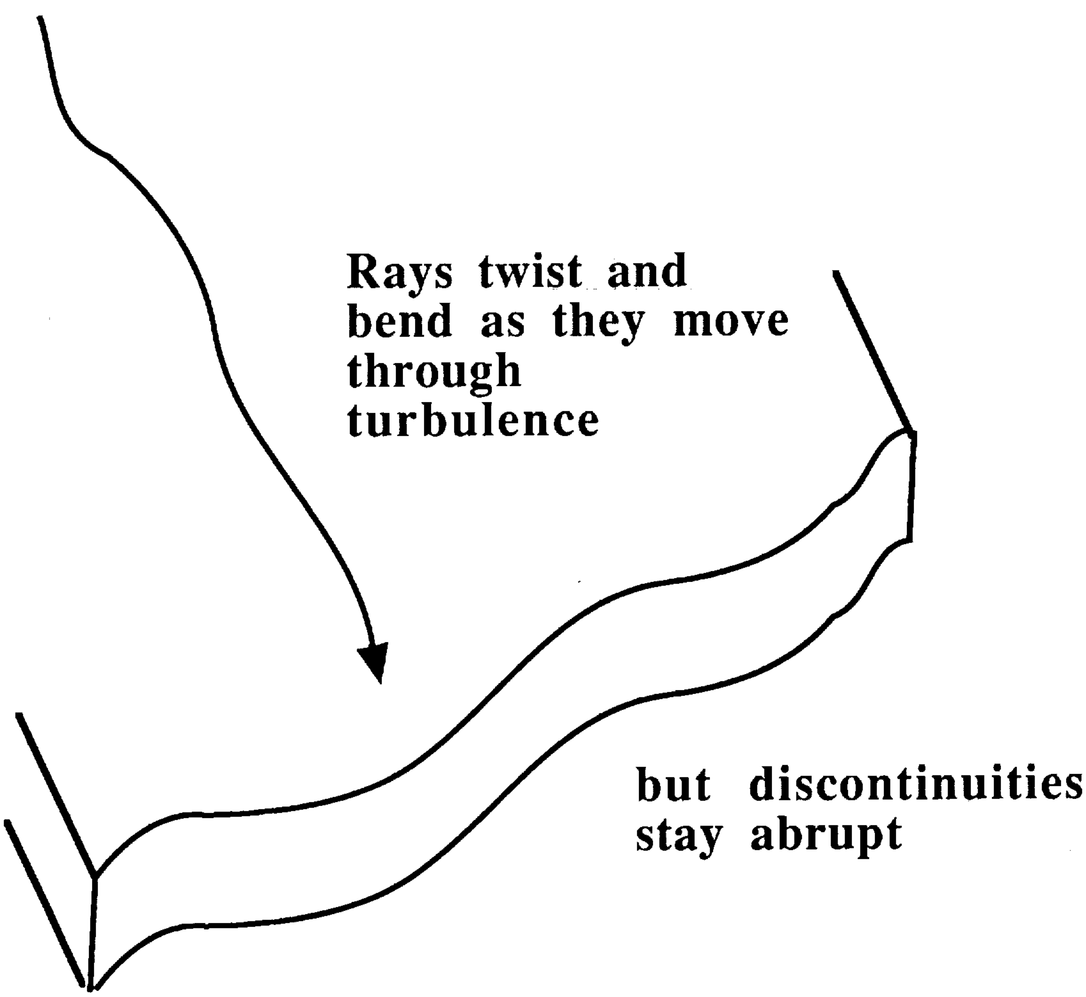
But not all parts of waveform are magnified

or demagnified equally.


p
Normal waveform
insensitive
to focusing
or defocusing
obeys
geometrical
acoustics
obeys
geometrical
acoustics
s
p
Spiked waveform
s
p
Rounded waveform
s

Paradox:

Why should turbulence affect thickness of shocks?



Luneburg-Keller ``theorem"

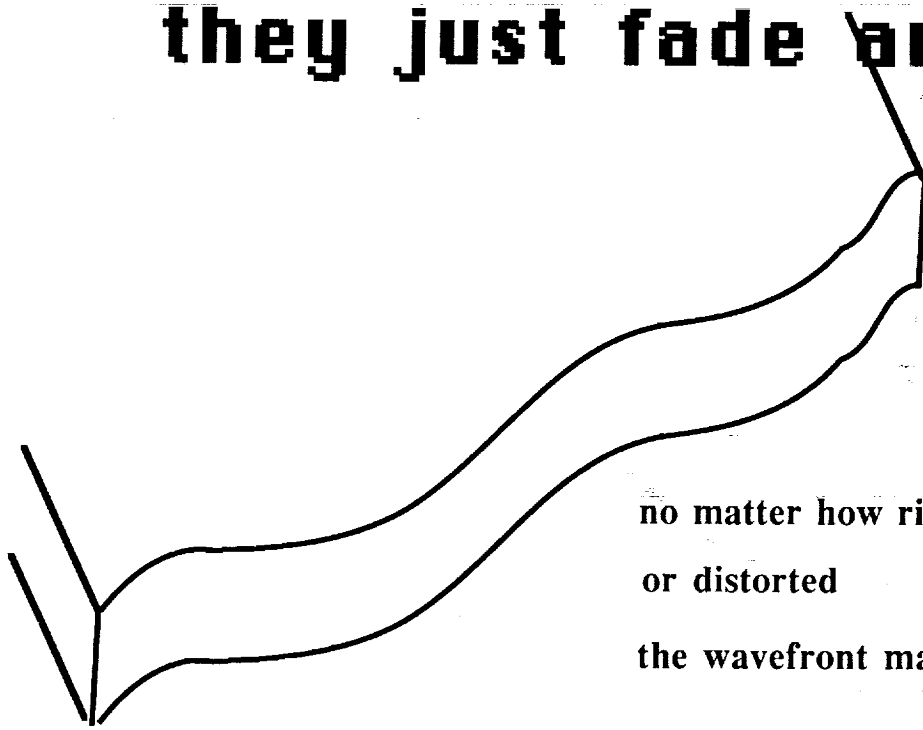
(also Christoffel, Love, Hadamard, Courant, Friedlander, Copson, Bremmer, possibly others)

Once a shock,

always a shock

Old shocks never die;

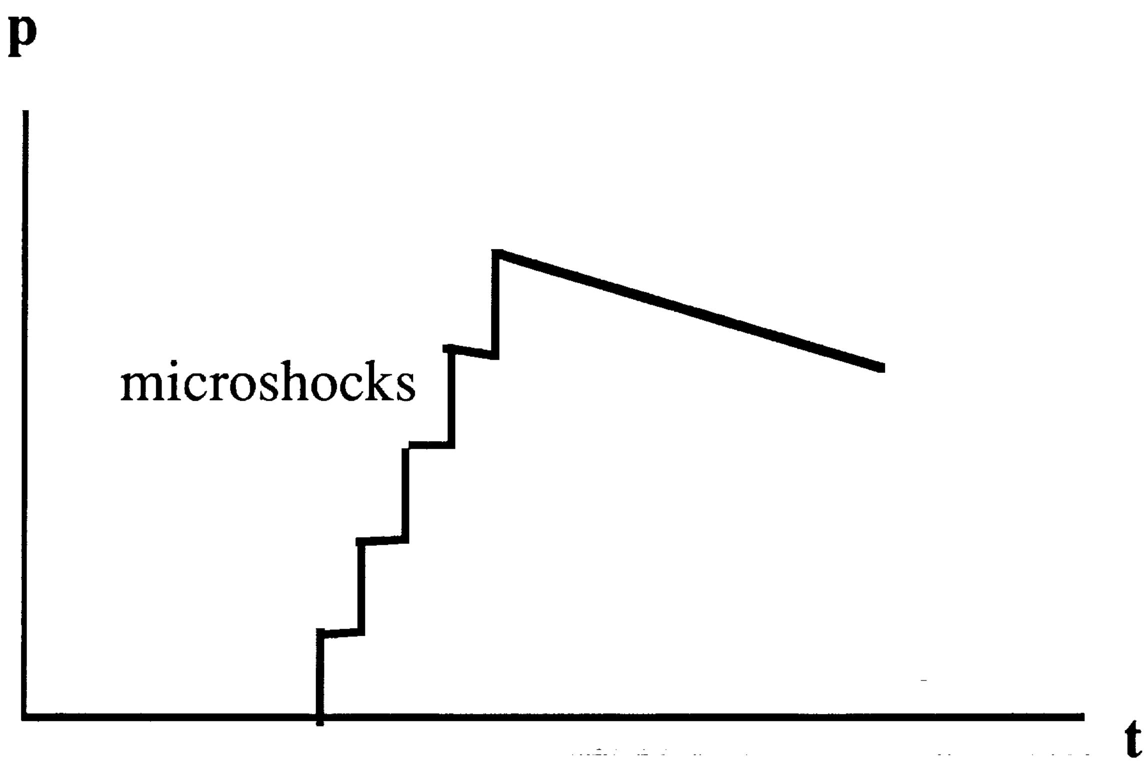
they just fade away



no matter how rippled

or distorted

the wavefront may be



Different rays arrive at closely spaced intervals.

Each ray carries its own microshock.

These build up to one big shock.

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