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Statistical and Numerical Study of the Relation Between Weather and Sonic Boom Characteristics

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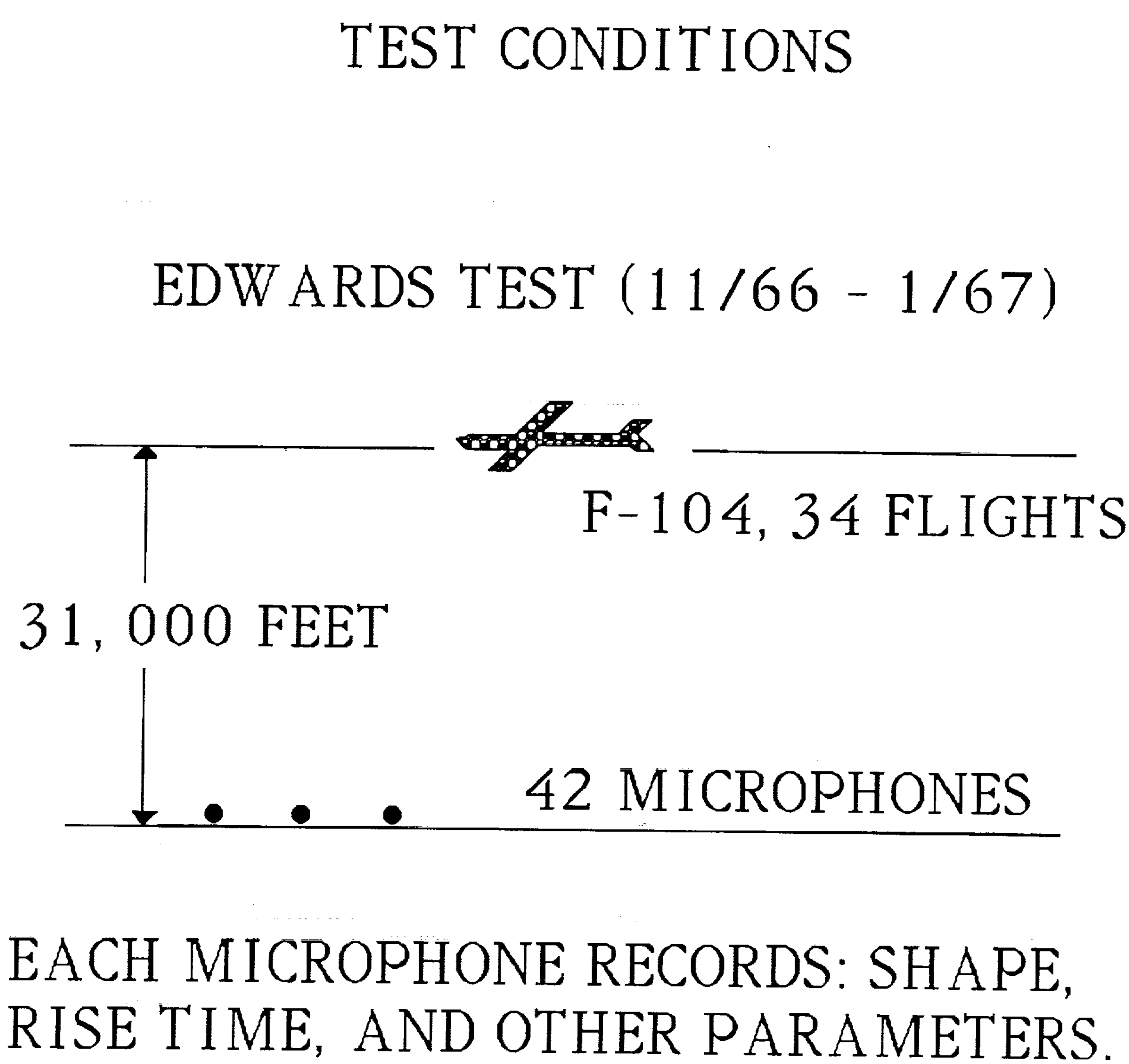
[redacted]TIONS OF EDWARDS TEST

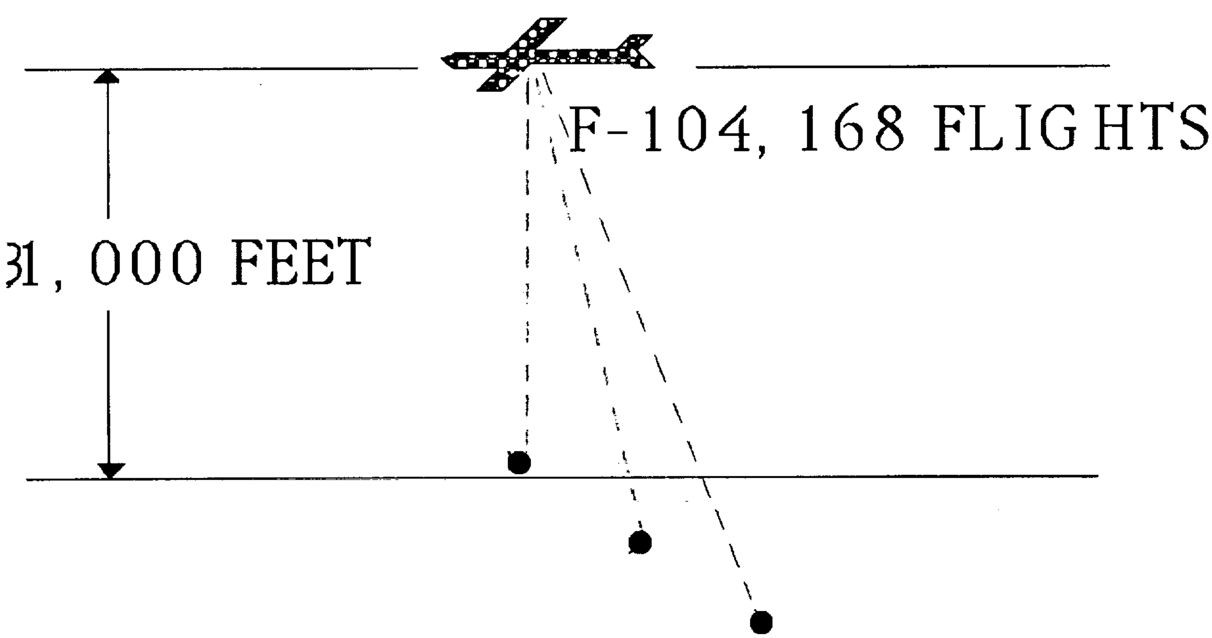
NASA measured sonic boom characteristics near Edwards Air Force Base from 11/66 to 1/67. 34 flights of F-104 were performed at an altitude of about 31, 000 feet and flying speed of Mach 1.3 . 42 microphones were placed on the ground directly under the fight track. Each microphone recorded boom shape, rise time, peak overpressure, total boom duration, positive duration and positive impulse.



TEST CONDITIONS OF OKLAHOMA CITY AREA TEST

Another test was performed in the Oklahoma City area from 2/64 to 7/64. Four types of aircraft flew at various altitude. Only the data obtained with F-104 at approximately 31, 000 feet have been analyzed in this study. There were 168 such flights. Three microphones were located on the ground, with one underneath, one at 5 miles lateral distance and the 3rd at 10 miles lateral distance. Same information of boom was recorded as in Edwards test.

OKLAHOMA TEST (2/64-7/64)



DEFINITION OF TURNER CLASS

Weather conditions including wind speed, temperature and cloud cover at the time of operation along with time of the flights were also recorded. From this information, a meteorological parameter called Turner Class can be derived. Turner Class has seven integer values, from 1 to 7, with 1 representing dominant convective turbulence, 4 for strong mechanical turbulence and 7 for stable stratification. Values between are mixing states of these three extreme conditions. Under fixed wind speed, when downward radiation increases, Turner Class shifts toward 1, when upward radiation increases, it approaches 7. Under fixed radiation index, when wind speed increases, the Turner Class approaches 4. Turner Class was calculated to indicate the turbulence condition at each flight time.

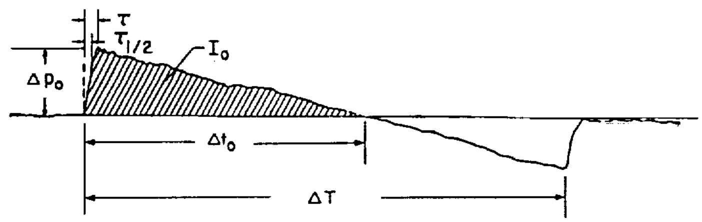
DEFINITIONS OF TURNER CLASSES

Wind Speed (knots)	Net Radiation Index: ← 4 (DOWNWARD RADIATION INCREASES)	3	2	1	0	-1	-2 → (UPWARD RADIATION INCREASES)
0-1	1	1	2	3	4	6	7
2-3	1	2	2	3	4	6	7
4-5	1	2	3	4	4	5	5
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8-9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
≥12	3	4	4	4	4	4	4

SONIC BOOM SIGNATURE PARAMETERS

Boom shapes were originally sorted into 10 types: N, NP, NR, P, PP, SP, SPR, PR, R and CO. They were grouped into three main categories in our statistical analysis, with N, NP to N-Wave Type, P, PP, SPR and PR to Peaked Type, and R and NR to Rounded Type. The 1st type is basically a N- wave. The 2nd type has an abrupt rise followed by an abrupt drop at the front shock. The 3rd type is much more rounded comparing with others. Rise times cover a wide range from 1 to 20 ms. They were also grouped into 4 major domains, with 1 covering from 1 to 5 ms, 2: 5 - 7 ms, 3: 7 - 9 ms and 4: 9 - 20 ms. The non-uniform grouping is based on the consideration that there should be a considerable occurrence for each domain. 7 wind speeds appeared in Edwards test: 0, 1, 2, 4, 5, 6, 7 and 16 knots. They were grouped too, with 11.5 (average value) representing 7 and 16, 5 for 4, 5 and 6, 1 for 0 and 2 knots.

Sonic Boom Signature Parameters



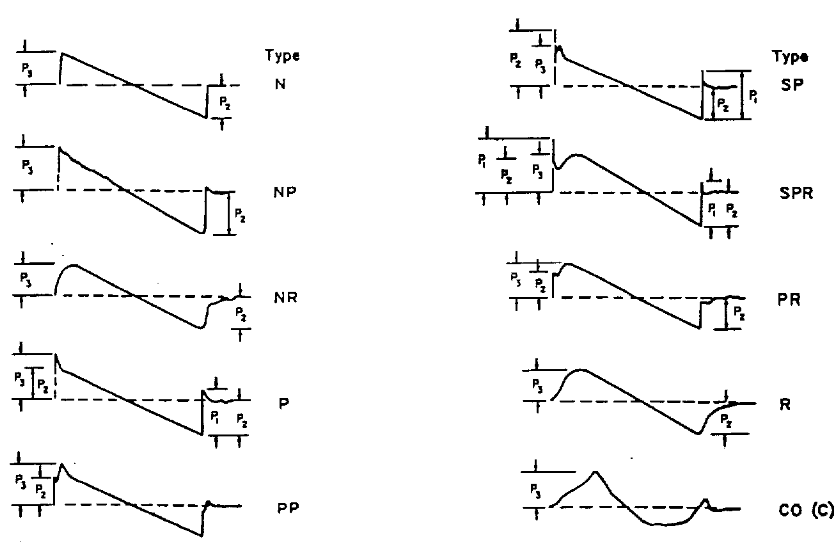


Fig Diagrams of waveforms which represent the various categories of measured sonic-boom signatures.

FREQUENCY TABLE OF TURNER CLASS AND RISE TIME

Each flight has a corresponding Turner Class. Each flight led to many shapes with varying rise times and other boom parameters. Thus, one certain Turner Class is associated with many rise times, which can be categorized into one of the 4 major domains and we can count how many rise times fall into each individual domain. In this way, a frequency table for Turner Class and rise time was generated. Only Edwards data were processed for this table. There were 1, 330 valid cases.

FREQUENCY TABLE OF TURNER CLASS AND RISE TIME

	Rise Time			
Turner Class	1	2	3	4
4	97	99	97	192
5	119	65	52	117
6	149	92	87	125
3	19	9	6	5

NORMALIZED FREQUENCY TABLE OF TURNER CLASS AND RISE TIME

Each row of the preceding table was normalized to give the following table. By doing this, we can see the distribution of rise times under each Turner Class. Note that for pure mechanical turbulence (Turner Class 4), there are more long rise times. When mechanical turbulence becomes less dominant (3) or damped (5, 6), there are more short rise times.

NORMALIZED FREQUENCY TABLE OF TURNER CLASS AND RISE TIME

	Rise Time			
Turner Class	1	2	3	4
4	0.20	0.20	0.20	0.40
5	0.34	0.18	0.15	0.33
6	0.33	0.20	0.19	0.28
3	0.49	0.23	0.15	0.13

NORMALIZED FREQUENCY TABLE OF TURNER CLASS AND WAVE SHAPE

A similar frequency table can be obtained for Turner Class and wave shapes, and row normalization can be done also. Only the normalized tables will be provided from now on. We see that weather conditions which result in strong mechanical turbulence give rise to the largest percentage of rounded wave shapes. When mechanical turbulence becomes less dominant (convective turbulence becomes more dominant, Turner Class 3,2,1) or damped (Turner Class 5, 6) this percentage decreases, while the N-wave type wave shape becomes more common until dominant. The table also shows that the peaked wave shapes are quite rare and occur most commonly for Turner Class 3 and 6. Turner Class 3 is mildly convective and Turner Class 6 is moderately stable. We speculate that the presence of peaked type wave forms is an indicator of large scale refractive structures in the atmosphere. The effects of these structures are overwhelmed by scattering from smaller scale mechanical turbulence as wind increases.

NORMALIZED FREQUENCY TABLE OF TURNER CLASS AND WAVE SHAPE

	Wave Shapes		
Turner Class	N-wave	Peaked	Rounded
4	0.26	0.04	0.70
5	0.34	0.06	0.60
6	0.21	0.12	0.66
3	0.46	0.13	0.41
2	0.80	0.00	0.20
1	0.86	0.00	0.14

ROW-NORMALIZED FREQUENCY TABLE OF RISE TIME AND WAVE SHAPE

Mechanical turbulence tends to increase rise time and induce rounded boom shapes according to previous tables, indicating the relationship between the two boom characteristics. This can be shown with another normalized frequency table for shape and rise time, (based on Edwards data). It is clear from the table that rounded wave shapes are associated with longer rise times (domain 4), while the peaked and N-wave types are more likely to have a shorter rise time (domain 1).

ROW-NORMALIZED FREQUENCY TABLE OF RISE TIME AND WAVE SHAPE

	Wave Shapes		
Rise Time	N-wave	Peaked	Rounded
4	0.06	0.05	0.89
3	0.08	0.05	0.87
2	0.19	0.07	0.73
1	0.59	0.12	0.29

NORMALIZED FREQUENCY TABLE OF WIND AND RISE TIME

Wind is an important factor in determining the Turner Class. We look specifically into the relationship between wind and rise time. A normalized table was obtained as following. The statistics shows that strong winds tend to associate with long rise times and weak winds are more likely associated with a short rise time. Similar statistics were examined for each Turner Class. There was no similar indication that strong wind has a trend to increase the rise time within a fixed Turner Class. The frequency tables for wind speed versus shape does not reveal any correlation.

NORMALIZED FREQUENCY TABLE OF WIND AND RISE TIME

	Rise Time			
Wind	1	2	3	4
11.5	0.16	0.16	0.22	0.46
5.0	0.33	0.18	0.17	0.32
1.0	0.30	0.25	0.18	0.27

INITIAL SHAPE OF SONIC BOOM

A physical model was established to investigate the propagation of a sonic boom through turbulence. We simulated the turbulent atmosphere with a distribution of spherical turbules randomly distributed in space (100 by 100 by 100 m, the turbules occupy 13% of the total volume of the space). An initial N-wave type boom shape is assumed, which is then Fourier transformed. The initial shape has a rise time of 0.2 ms. (defined as from onset of shock to the maximum peak overpressure) Each frequency component (spherical wave) is first order scattered by each turbule under Rytov approximation and the scattering waves from all of the turbules are summed to give the amplitude and phase of the pressure of this particular component at the receiver. An inverse Fourier transform is then applied to obtain the boom shape at the receiver.

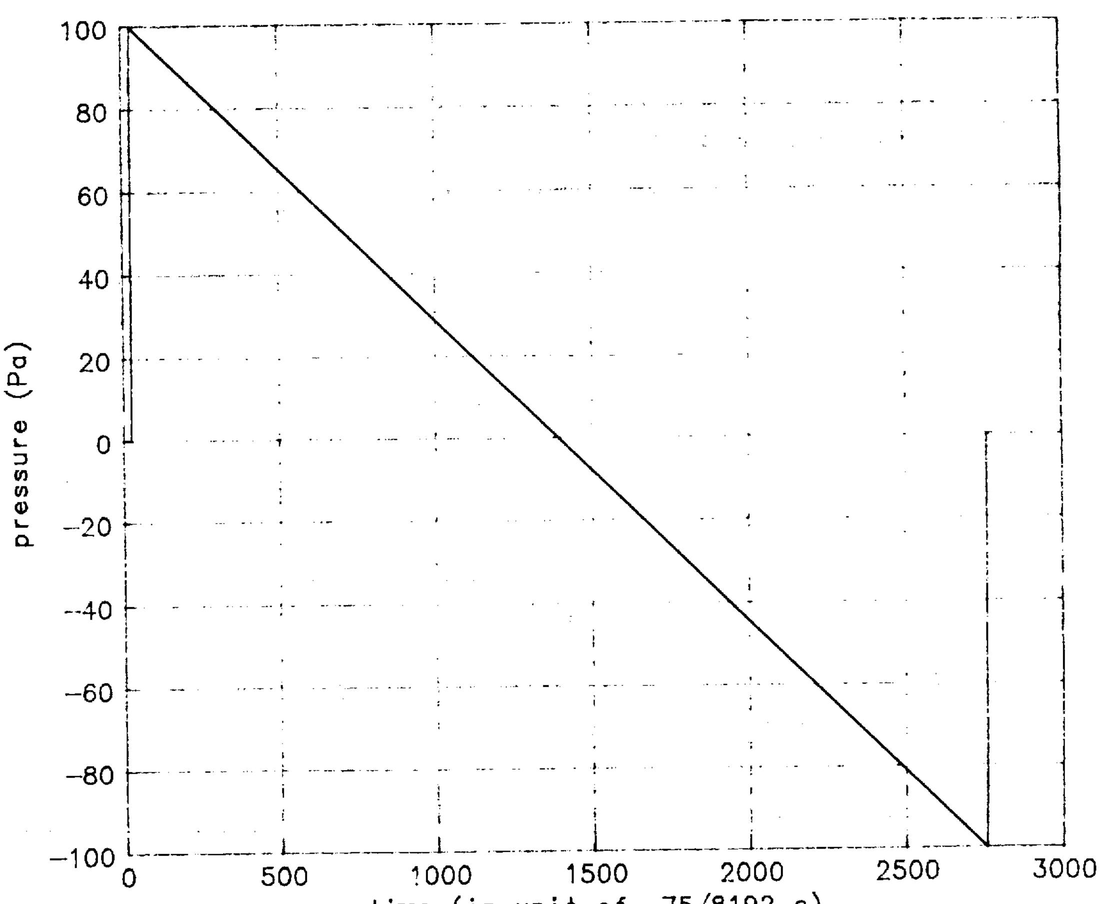


Fig INITIAL SHAPE OF SONIC BOOM

SHAPE FROM REALIZATION 8 FOR TURBULE SIZE OF 1 M

32,000 turbules with radius 1 m are randomly distributed in the 100 by 100 by 100 m space. The resulting shape at the receiver 100 away from the source is simply a N-wave type. This shape has rise time of 1.282 ms. We see that the turbulence represented by this configuration does not deform the original shape except that some small wiggles are added to the boom.

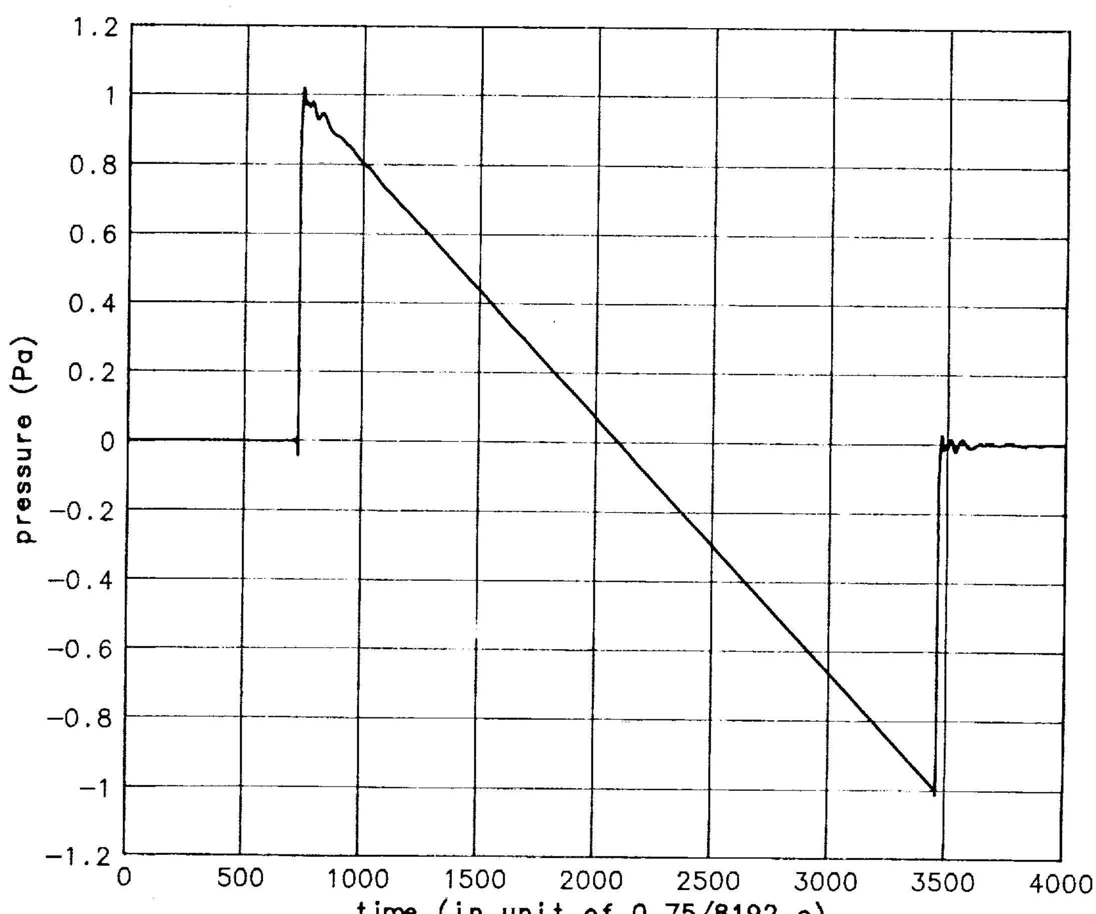


Fig SHAPE FROM REALIZATION 8 FOR TURBULE SIZE OF 1 M

SHAPE FROM REALIZATION 6 FOR TURBULE SIZE OF 10 M

32 turbules with radius 10 m are randomly distributed in the space. The final shape belongs to the PR type, with a rise time of 10.254 ms. Here the effect of turbulence is obvious, the shape becomes rounded and the rise time is much increased. The expected rise time due to molecular relaxation is on the order of 1-3 ms.

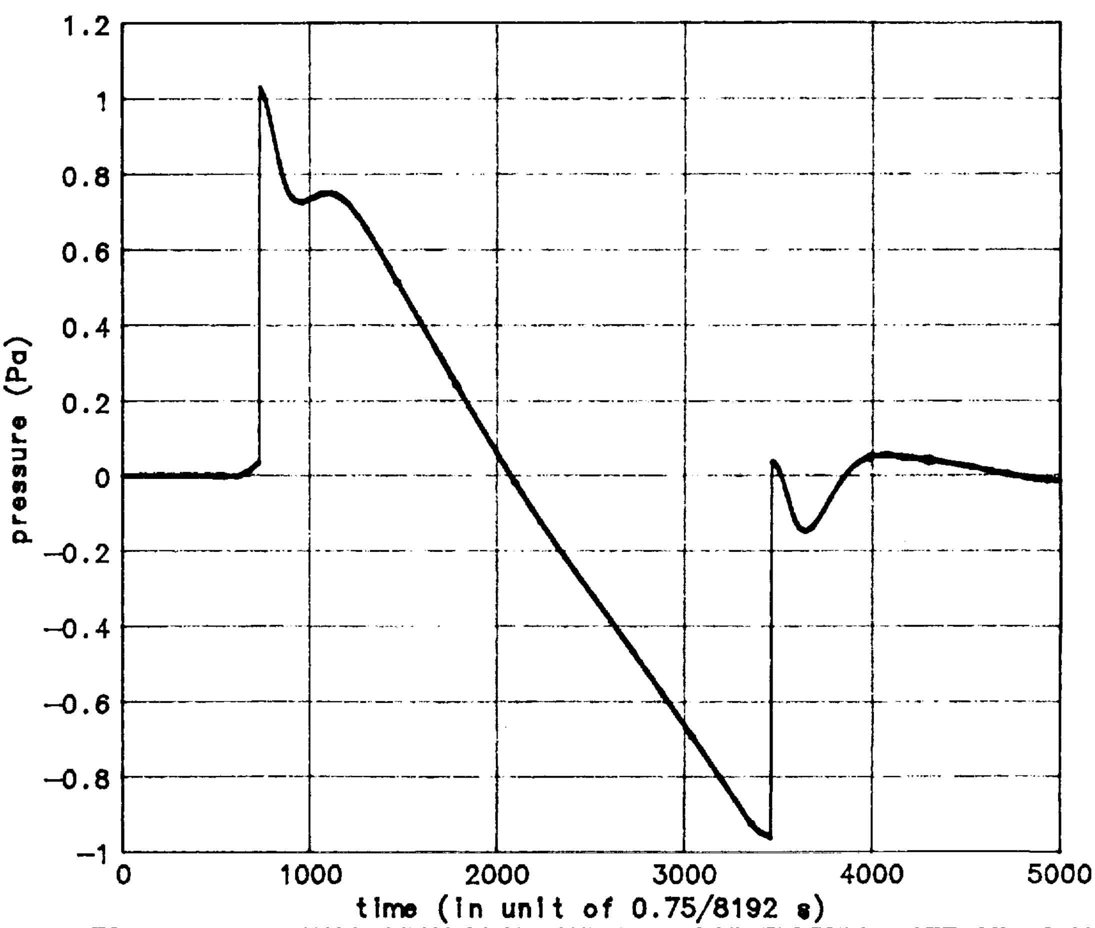


Fig SHAPE FROM REALIZATION 6 FOR TURBULE SIZE OF 10 M

SHAPE FROM REALIZATION 8 FOR TURBLUE SIZE OF 10 M

One more realization of 32 turbules generates the following R type boom shape. The rise time is 16.479 ms. The turbulence makes the shape very rounded and the rise time very long, up to the order of long rise times really observed in the previously described tests.

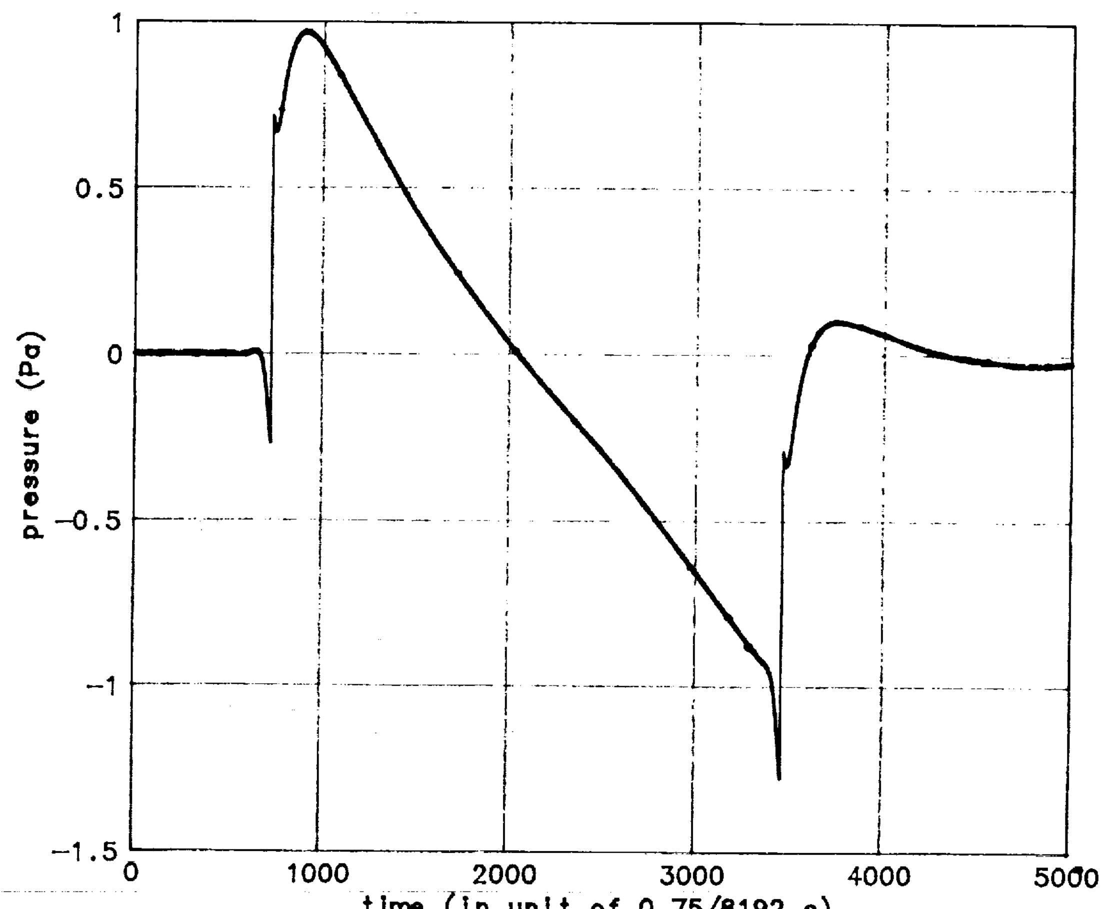


Fig SHAPE FROM REALIZATION 8 FOR TURBULE SIZE OF 10 M

SHAPE FROM REALIZATION 7 FOR TURBULE SIZE OF 10 M

Another realization of 32 turbules gives the following shape. The amazingly strong wiggles at both the front and the back shock are very impressive. The rise time of this shape is 4.578 ms. The details of front and back shock are shown by the two pictures following this one. The symmetry between the front shock and the back shock is consistent with the feature of the shapes observed.

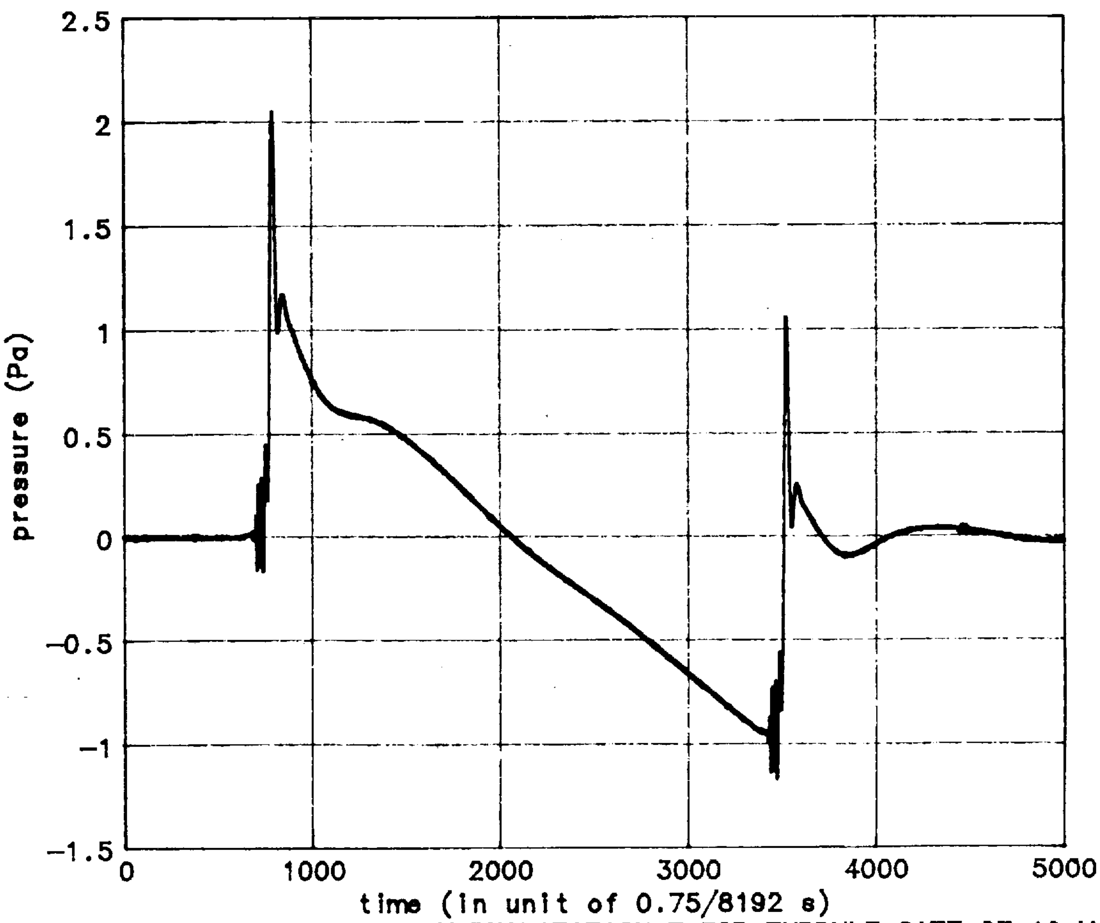


Fig SHAPE FROM REALIZATION 7 FOR TURBULE SIZE OF 10 M

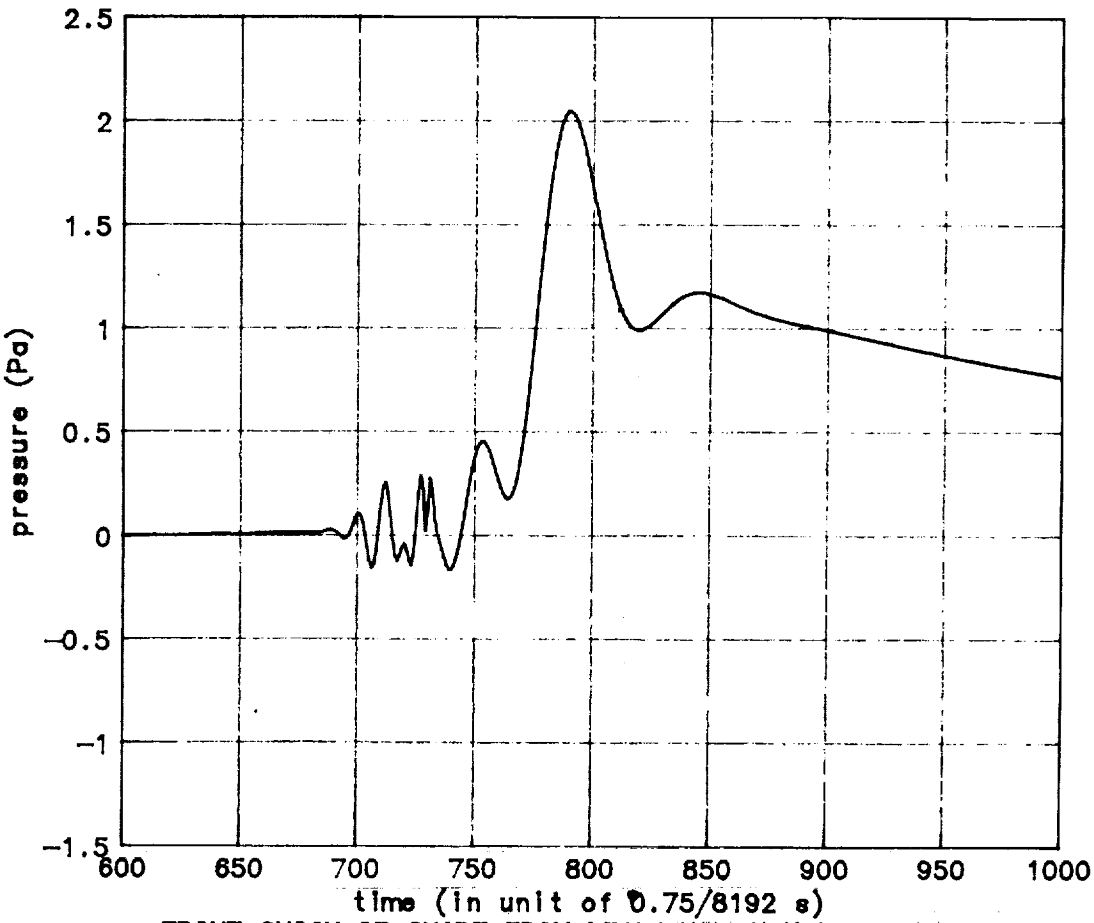


Fig FRONT SHOCK OF SHAPE FROM REALIZATION 7 FOR TURBULE SIZE OF 10 M

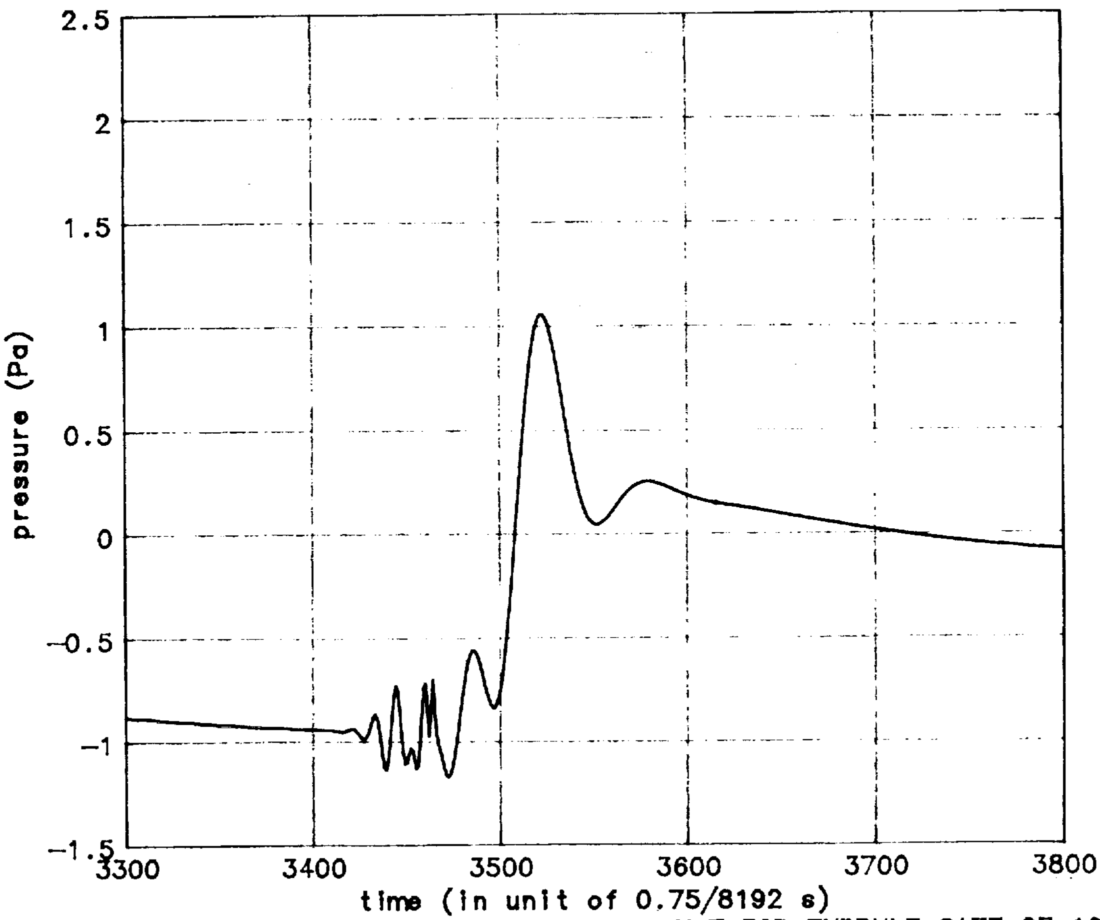


Fig BACK SHOCK FROM REALIZATION 7 FOR TURBULE SIZE OF 10 M

CONCLUSION

1. Turbulence and sonic boom propagation are related.

2. Strong mechanical turbulence is associated with long rise times and rounded boom shapes.

3. Presence of convective turbulence or stable stratification is associated with short rise times and N-wave type shapes.

4. Since rise time is both sensitive to wind and Turner Class, while boom shape is only correlated with Turner Class, rise time can be considered a more suitable indicator to judge the influence of turbulence (mechanical).

5. Numerical calculation based on a turbulence scattering model does predict the rounded wave shapes and long rise times, which is consistent with above statistical conclusion. We infer that pure mechanical turbulence has the proper turbule size which results in these rounded type shapes, while strong convective turbulence does not. Stable stratification certainly is not involved with turbulence and N-wave type shapes are expected to be observed at the receiver.

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