Sound Generation by Explosive Decompression of an Airplane

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Abstract. We examine sound generation by the explosive decompression of a pressurized airplane in flight. The near-field is numerically computed by assuming the sudden removal of an axial section of an idealized, streamlined, cylindrical fuselage with an external flow simulating flight. After an initial transient period, we find a nearly circular blast wave with a leading shock strength that is highest in the direction of motion and decreasing rapidly as the observer moves to the rear of the airplane. Geometric acoustics (ray tracing) is used to estimate the attenuation of the wave as it propagates through a model atmosphere to observers on the ground. The audibility of the event is examined in the case of the TWA 800 accident and compared to previous analyses.

1 Introduction

The occupied portion of the fuselage in a commercial airplane is pressurized to maintain a minimum oxygen concentration for the passengers. If a portion of the fuselage suddenly fails, then the gas inside will rapidly expand into the surrounding atmosphere, producing a shock wave and flow through the opening. The shock wave will be convected and refracted as it propagates through the atmosphere. When the resulting blast wave reaches the ground, it may be heard by observers as a loud noise, or possibly, recorded on seismic monitors [7]. The present study is motivated by the observations that were reported following the in-flight breakup of a Boeing 747 in 1996 [3]. The goal of the present study is to use computational methods to predict the order-of-magnitude of the blast amplitude at the ground.

The computations proceeded in two steps. First, we carried out a axi-symmetric numerical simulation of the gasdynamics close to the rupture (near-field) in order to obtain the amplitude of the leading shock wave at a distance of about 10 radii from the fuselage. Second, we performed a geometrical acoustics computation of the wave far from the fuselage (far-field), tracing rays through a realistic stratified atmosphere and estimating the amplitude of the leading shock wave when it reached the ground. Finally, we consider our results in view of the reported observations and other analyses of this event.

2 Numerical Simulation of Near-Field

We have carried out a numerical simulation of explosive decompression to compute the near-field pressure distribution. The simulation solved the Euler equations for a perfect gas using the adaptive mesh refinement software of [5]. The airplane fuselage was idealized as a cylinder of constant cross section. The flow outside the fuselage simulated the conditions of the 747 breakup mentioned above: a flight altitude of 4.2 km, ambient temperature of 260 K, ambient pressure of 0.585 bar, and a flight Mach number of about 0.50.

First, the flow around the fuselage was set up by carrying out a shock tube simulation and arranging for the fuselage to be surrounded by the uniform region between the contact surface and expansion fan. Second, once a steady flow had been established around the

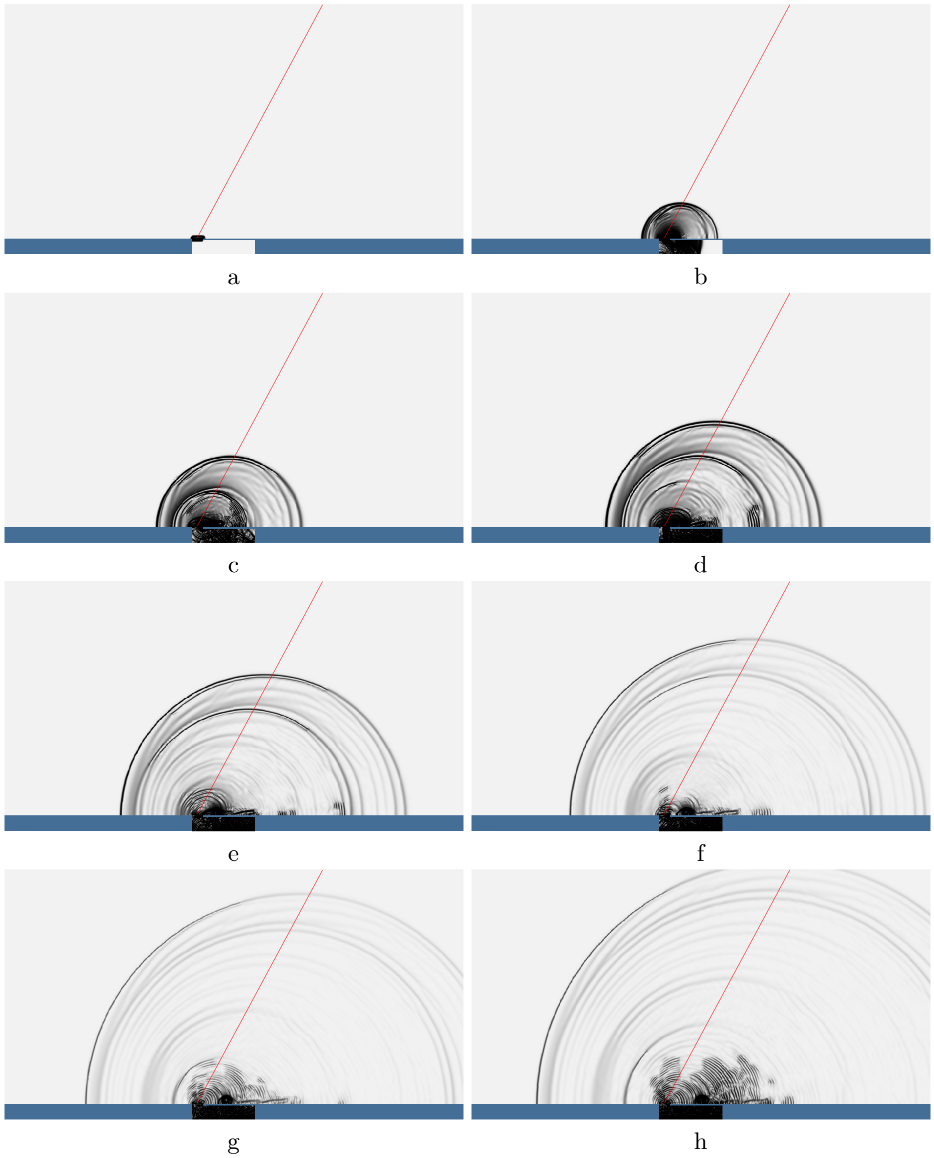

Fig. 1. Blast wave propagating into $M = 0.5$ flow after simulated explosive decompression of an airplane fuselage at an altitude of 4.2 km. Flow is from left to right. The bottom of the image coincides with the axis of symmetry of the fuselage model.

fuselage, a portion of the fuselage was replaced by a pressurized gas cylinder of the same diameter.

A circumferential section of the fuselage that is one-half diameter long was suddenly removed to simulate the explosive decompression. This is analogous to the ideal opening of the diaphragm in a shock tube. The pressure inside the aircraft was estimated [10] to be about 3.5 psi (0.24 bar) higher than the external pressure at the time of the decompression. Based on this, the conditions in the pressurized volume were chosen to be a pressure of 0.823 bar and temperature of 295 K; the volume of the pressurized portion was 1000 m^3, representative of the pressurized volume of a large commercial transport like a 747. The geometry of the simulated fuselage and the blast wave are shown in Fig. 1. The initial shock wave created when the fuselage ruptures can be computed using the standard shock tube analysis [8] to have a pressure jump of 0.11 bar and induce a velocity of 40 m/s at the opening. This initially cylindrical shock diffracts, forming an expanding blast wave that weakens as it propagates away from the fuselage.

The sequence of images in Fig. 1 shows that the blast wave is very nearly spherical but the center is displaced downstream due to the external flow of 160 m/s. The leading pressure wave has an N-wave profile with a peak amplitude that is strongly dependent on the direction. The wave front directly ahead of the airplane has the largest amplitude and the amplitude decreases monotonically sweeping around the wave to the rear of the airplane. An example spatial profile along a line 60.7° measured clockwise from the rear of the fuselage (shown extending from the fuselage opening in Fig. 1) is shown in Fig. 2a. The peak overpressure ΔP of the leading shock is shown as a function of angle in Fig. 2b.

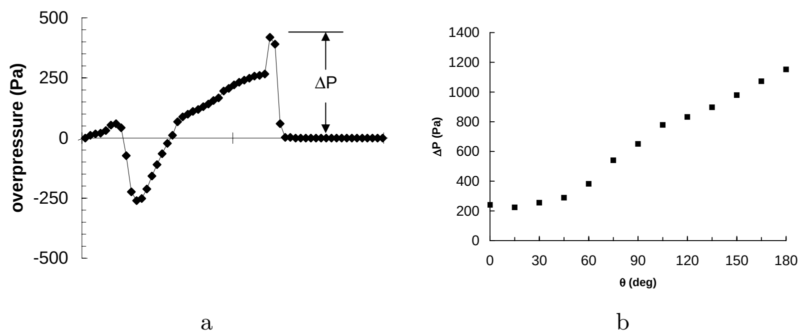

Fig. 2. a) Spatial profile of the leading N-wave of the blast wave front propagating at 60.7° to the fuselage. This corresponds to the ray shown in Fig. 1f; the leading shock front is about 50 m along the ray from the fuselage. b)Variation of peak shock overpressure with angle on a sphere 50 m in radius.

As expected, the maximum shock overpressure of 1.15 kPa is located at the front (upwind or 180°) side of the shock and the minimum of 0.2 kPa is at the rear (downwind or 0°) side. For comparison, if the fuselage were treated as an ideal bursting sphere of pressurized gas in a stationary atmosphere, the correlation of Vanderstraeten et al. [9] predicts that the initial shock overpressure at 50 m would be 2.6 kPa, independent of orientation. The lower shock overpressure for the rupturing fuselage is due to the small open area in comparison to the envelope of the sphere with the same volume while the angular dependence is a consequence of the asymmetry produced by the motion of the air relative to the fuselage.

In addition to computations shown in Fig. 2, several variations were carried out to examine the sensitivity of the results to geometry and solver type. The initial shock overpressures were within 10% for a linearized solver of the Roe type (results shown in Figs. 1 and 2) and also a Kappa-Muscl HLLE solver. A computation with a finite rounded nose ahead of the rupture was carried out and the only difference was that the displacement effect of the finite fuselage increased the upstream pressure ahead of the blast wave for angles greater than 120°. However, the shock overpressure distribution at 50 m was not significantly different from the case of the infinite length fuselage model.

3 Numerical Computation of Far-Field

In order to compute the amplitude at the ground, it is necessary to compute the effect on the blast wave of propagation through the atmosphere. We did this by using the method of geometrical acoustics (see Chap. 8 of Pierce[4]), a standard technique used for sonic booms [7] and high altitude explosions of weapons [1]. The computation proceeds by considering the propagation of the wave front using ray tracing and determining the variation of the amplitude through energy conservation. The method of ray tracing is based on constructing the path of a point X on a wavefront using the following extension of Huygens' principle

$$\frac{d\mathbf{X}}{dt} = \mathbf{v} + \hat{\mathbf{n}}c \tag{1}$$

where $\mathbf{v}$ is the local wind velocity, c is the sound speed, and $\hat{\mathbf{n}}$ is the local normal to the wavefront. The right hand side of Eq. 1 is known as the *ray velocity*. The geometric construction of the ray velocity and three sample rays are shown in Fig. 3.

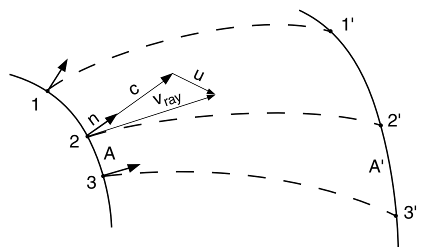

Fig. 3. The geometry of wave fronts, rays, and the construction of the ray velocity due to sound propagation and convection by the wind.

The input to the ray tracing computation was the approximate distribution of amplitude at 50 m (Fig. 2b) as determined by the near-field simulation. Our computation includes the refraction of the rays due to sound speed variations, convection of the rays due to the wind, and the variation in the amplitude due to the ray tube area increase between the source and the ground. The properties of the atmosphere were those appropriate for TWA 800 as measured by a weather balloon slightly before the accident, see Exhibit 5A of [3]. The most important environmental factor for the ray-tracing computation is the sound speed variation with altitude, which decreases nearly linearly with increasing altitude (Fig. 4a). As a consequence, if we neglect the various modest amounts of convection, the rays originating at a point above the surface take the form of circular arcs (Fig. 4b) when viewed from the side.

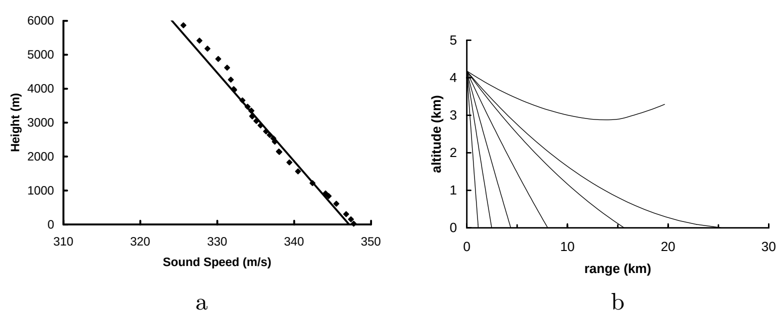

Fig. 4. a) Spatial profile of the sound speed in the atmosphere from the weather balloon data for TWA Flight 800. b) Examples of rays obtained by neglecting convection by the wind.

As a consequence of the refraction of the rays due to the sound speed gradient, rays from an explosion occurring at an altitude z above the surface will reach the surface only inside a circular region centered on a point beneath the explosion. Outside of this region is the geometric "shadow region" or "zone of silence" and according to the geometric model of sound propagation, observers in this region should not be able to hear the explosion. In reality, observers in the shadow region may hear the explosion due to diffraction, scattering, and variability in the atmosphere. In the case of the TWA 800 event, the shadow zone was about 27 km in radius, shown as a circle on Fig. 5) .

The amplitude (ΔP shown in Fig.2a) of the blast wave when it reaches the ground can be determined by using the conservation of energy along the rays. The general case of a moving atmosphere can be handled through the use of the *Blokhinstev Invariant*, see Pierce [4], pp. 399-406; in the case of negligible wind this reduces to

$$\Delta P \left(\frac{A}{\rho c} \right)^{1/2} = \text{constant} \tag{2}$$

where A is the ray tube area and ρc is the acoustic impedance. In the idealized case of spherical spreading, the ray tube area increases with s^2 where s is the radial distance from the explosion - this leads to the well-known acoustic decay law $\Delta P \sim s^{-1}$ associated with the wave front spreading. A further refinement would be to consider the effect of weak nonlinearity [4], which is known to slightly increase the decay rate to $\Delta P \sim s^{-1}(\ln s)^{-1/2}$ in the far field. Combining the notion of ray tracing with amplitude variation along the rays, we have computed the propagation of the spherical wavefront obtained by the near-field computation to the ground level. The resulting pattern of constant peak pressure contours is shown in Fig. 5. As shown, the distribution of peak pressure is highly biased along the direction of the flight path due to the initial conditions of Fig. 2b.

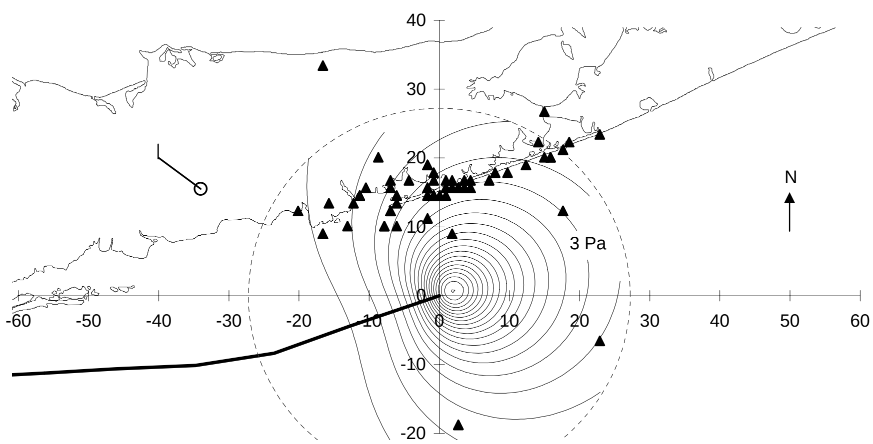

Fig. 5. The coastline of Long Island, flight track of TWA 800, contours of predicted blast overpressure at 0.5 Pa increments starting at 1 Pa and ending at 10.5 Pa, and locations of some witnesses [2] who heard sounds. The coordinates are given in km with the origin centered at the last reported primary radar return - the track of the airplane is shown as the thick line. The dashed circle indicates the boundary of the shadow zone. A wind vector indicates the average direction and speed observed by the weather balloon.

4 Conclusions

This analysis was motivated by previous work [6,2] on the sounds heard accompanying the in-flight breakup of TWA 800 in 1996 [3]. One or more sounds variously described as an “explosion, boom, concussion, rumble, thunder” were heard by 239 of the 736 witnesses, mostly located along the south shore of Long Island, NY about 15 to 20 km (slant) range from the aircraft’s position at the time of breakup (Fig. 5).

Unfortunately, there are no barograph or seismic records from the TWA explosion and we have only the descriptions of what the witnesses reported that they heard. Reed [6] has examined the witness reports and considered these in view of his experience with high explosive air blast. He concluded that the peak air blast pressure must have been at least 20 Pa (120 dB) in order to be consistent with the perceived loudness by the witnesses. Using the standard methodology [1] for high-explosive air blast propagation predictions, Reed estimates that an equivalent energy release of 1-tonne of TNT would have been required to produce an overpressure of 20 Pa at 15 km range. McAnich et al. [2] examined a subset of the witness locations within 20 km of the event and used several methodologies to predict overpressures for these locations. They concluded that an explosion with an energy equivalent of 9 kg TNT would have been audible to all observers within 30 km except those in the “shadow” zone. Their definition of audibility was based on a spectral analysis of the predicted blast pressure time history and the nominal hearing threshold based on typical residential background noise for specific human subjects. They predict a peak overpressure of 8.6 Pa (112 dB) for an observer at 19 km slant range. Both studies consider a conventional single-peak blast wave pressure pulse rather than the N-wave predicted by the present study.

Our computations indicate that a previously neglected mechanism, explosive decompression, may also provide an explanation for the source of some of these sounds. Our computations indicate that an N-wave blast profile (similar to a sonic boom) with an initial shock overpressure of about 3.5 kPa (105 dB) would have been produced at the location of the nearest observers on the shoreline. Although lower than the values suggested by previous analyses, this would have been audible to many of these observers. The blast wave from explosive decompression is predicted to be highly anisotropic, with the amplitudes in the direction of travel up to six times higher than behind the aircraft at the same slant range.

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