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AERODYNAMIC NOISE: A CRITICAL SURVEY

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Annoyance due to railway noise is a particularly sensitive aspect of new high-speed projects. Many studies have shown that aerodynamic noise becomes significant above 300 km/h and can become predominant with the reduction of the contribution of rolling noise. At the moment, no further global reduction of high-speed train noise can be achieved if the aerodynamic noise is not reduced. The objective of this paper is to provide a critical survey of the aeroacoustic noise problem for trains, particularly for high-speed trains. The first step in any acoustic study is to identify the different sources. This paper describes the different aeroacoustic phenomena which are representative of high-speed trains and the technical methodologies used to characterize these phenomena. Specific tools have been developed from on-line tests, wind tunnel experiments, theoretical studies or numerical simulations to characterize the different sources. Using examples, the limitations of the methods and the solutions currently available are reveiwed today. Methods of global modelling of a high-speed train emission are also presented. Finally, future development of new tools based on numerical simulation in aeroacoustics are discussed.

1. INTRODUCTION

Annoyance due to railway traffic noise is a particularly sensitive aspect of new high-speed projects. For conventional trains operating at a maximum speed of up to 200 km/h and for high-speed trains at speeds upto 300 km/h, the overall sound is dominated by rolling noise. Rolling noise is generated by wheel/rail interaction, which, in addition to causing airborne sound, also transmits vibrations to other parts of the train. A survey on rolling noise investigations is given in reference [1]. Many studies [2] have shown that aerodynamic noise becomes significant above 300 km/h (see Figure 1). Mechanical noise essentially represents the rolling noise. Recent improvements in rolling noise have the effect of lowering the transition speed (U_t) which represents the change from the dominance of rolling noise to that of aerodynamic noise. Aerodynamic noise therefore could even become more predominant over rolling noise at 300 km/h. This transition speed is around 225 km/h for Maglev vehicles (mechanical noise for Maglev vehicles is due to the vehicle/guideway interactions).

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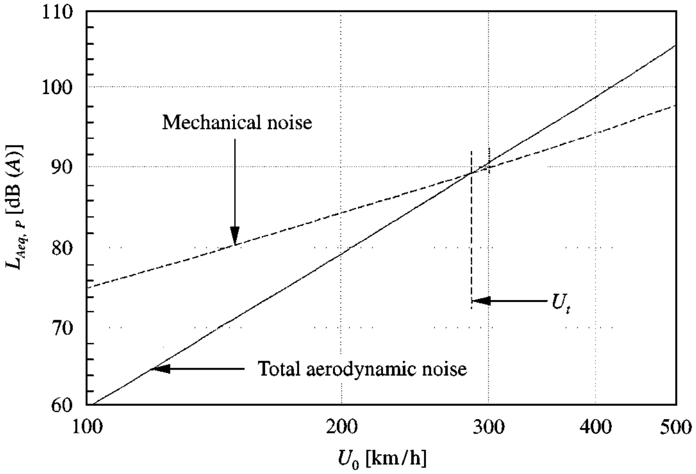

Figure 1. Transition speed U_t for a high-speed wheeled train (ICE or TGV) with an average level of rolling noise.

For several years, railway companies have been aware that no global reduction in noise level could be achieved if the aerodynamic noise is not reduced.

The objective of this paper is to provide a critical survey of aeroacoustic noise for high-speed trains.

The first step in any acoustic study is to identify the different sources. This paper describes the different aeroacoustic phenomena representative of high-speed trains and the technical methodologies used to characterize these phenomena. Specific tools have been developed from on-line tests, wind tunnel experiments, theoretical studies or numerical simulations to characterize the different sources. Using examples, the limitations of the methods are surveyed and solutions currently available are presented. Methods of global modelling of a high-speed train emission are also presented. Finally, future development of new tools based on numerical simulation in aeroacoustics will be discussed.

2. AEROACOUSTICS FOR TRAIN APPLICATIONS

On a moving train, a complex turbulent flow develops, interacting with a number of structural elements such as bogies or pantographs. For the train application considered here, the case of sound generated by turbulence in the absence of solid bodies (jet noise) is not included. The noise emitted by the train due to the turbulent flow can be separated into the noise radiated directly by the flow and the noise generated indirectly by the vibration of the surfaces excited by the flow. Hereafter, only the noise radiated *directly* by the flow including interactions with train surfaces considered as *solid* will be considered. One of the most important difficulties in aeroacoustics is that the sources are situated in the same medium as the propagation and it is not always easy to separate the source region, where the pressure fluctuations are aerodynamic, from the propagation region, where the pressure fluctuations are acoustical.

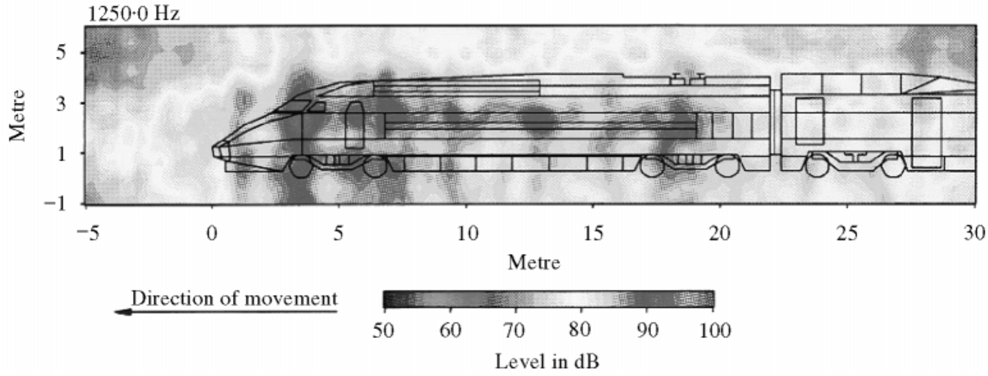

Figure 2. Map of aeroacoustic sources on a TGV obtained by antenna measurements.

3. IDENTIFICATION OF AERODYNAMIC SOURCES ON HIGH SPEED TRAINS

The first step in any acoustic study is to identify the different sources and the method for train applications is to carry out wayside noise measurements with devices such as antennae. An acoustic antenna is a series of microphones, whose outputs are processed in order to focus on acoustic sources and to enable an acoustic map to be drawn, as shown in Figure 2. Accurate measurements on high-speed train usually require the development of specific tools [3–6]. On-line acoustic measurements can be made using LASER Doppler velocimetry on board a high-speed train [7] which provides a description of the flow (mean velocities and statistical aspects of turbulence) and provides more information on steady sources.

The main aeroacoustic sources identified from different studies on various high-speed trains [5,8–10] (mainly Shinkansen, TGV, ICE, MAGLEV) are (with more or less significance of each source contribution depending on shape and technology of the train):

- ○ the pantograph
- ○ the recess of the pantograph
- ○ the inter-coach spacing
- ○ the bogie
- ○ the nose of the power car
- ○ the surfaces
- ○ the rear power car
- ○ louvres
- ○ ventilators

Noise generated by these different sources can be grouped according to two types of phenomena:

- ○ noise generated by flow over structural elements:
  - ● vortex shedding: pantograph and equipment
  - ● cavity noise: recess of the pantograph, inter-coach spacing, louvres
  - ● bogie
  - ● ventilators

- ○ noise generated by turbulent flow
  - turbulent boundary layer: surfaces
  - boundary layer separation: nose of the power car
  - unsteady wake: rear power car.

4. DEVELOPMENT OF TOOLS TO CHARACTERIZE DIFFERENT SOURCES, SOLUTIONS AND LIMITS

4.1. NOISE GENERATED BY FLOW OVER STRUCTURAL ELEMENTS

4.1.1. *Vortex shedding sound*: *pantograph and equipment*

As illustrated in Figure 3, noise barriers along the track do not shield aerodynamic sources on the roof such as pantographs and it is necessary to reduce the noise from these sources in order to reduce the overall noise [11].

Aerodynamic noise from the pantograph is generated by unsteady air flows induced by the various structural components of pantograph. Some components generate broadband noise [12] but generally they create aeolian tones clearly identified by their frequency peaks. The mechanism is characterized by periodic vortex shedding. When vortices break away from the surface of a slender body, they impact on the surrounding fluid. Because of the fluctuating nature of the vortex shedding process, the generated force also fluctuates at the same frequency as the vortex shedding. A fluctuating force creates dipole sound. The frequency, f, of the vortex shedding, the resulting fluctuating force and the aeolian tones can be characterized by a Strouhal number $\mathrm{St}_l = fl/U_0$, l being a characteristic length of the body and U_0 the external flow velocity. This vortex shedding appears generally at a Reynolds number (called critical Reynolds number $\mathrm{Re} = U_0 l/\upsilon \approx 3 \times 10^5$, v being the cinematic viscosity of the fluid) which is representative of a transition regime to turbulence but which can also appear at a lower Reynolds number if the cylinder is rough because the boundary layer becomes turbulent at lower speeds.

This generating mechanism is well understood as a result of investigations in wind tunnels and practical techniques have been developed to control and abate

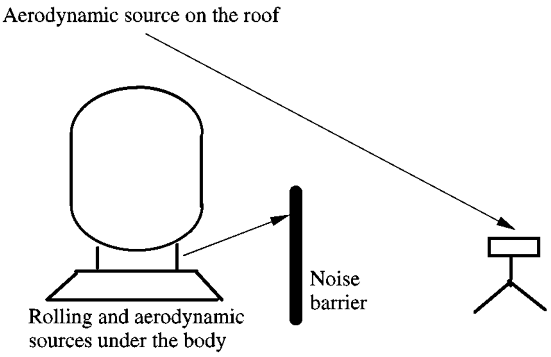

Figure 3. Schematic diagram for measurement of noise from high-speed train.

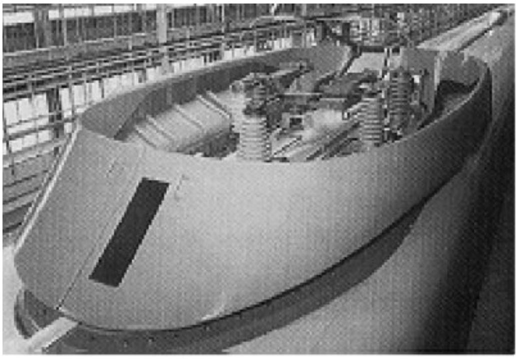

Figure 4. Pantograph cover of series 700 prototype.

this type of aerodynamic noise [13,14]. Field measurements results have been compared with wind tunnel measurements in several studies [2,15]. Although the phenomenon is currently well known and can be measured, a substantial reduction obtained in wind tunnel measurements may not be achieved on operating trains, possibly due to a combination of other sources.

The use of a pantograph cover has been shown to be effective in reducing this noise. The front edge of the cover reduces the velocity of the separating flow and the sides can be considered as noise barriers.

However, aerodynamic noise is generated by the cover itself. The most suitable combination of pantograph and cover has to be found. One example of an optimized cover for the Japanese series 700 prototype [16] is shown in Figure 4.

Further studies were carried out to examine the flow around electric isolators which are in the pantograph area and which contribute significantly to the noise. The flow regimes which can appear around these elements are not necessarily vortex shedding; irregularities on the cylinders of the isolators can also create local jets.

Some studies have also been carried out to optimize the pantograph itself. For example, wing shape collector heads has been developed [17]. Here, the optimum collector shape could be characterized from wind tunnel investigations. However, the best acoustic solution must also maintain good current collector properties at high speed.

For trains such as TGV, the pantograph is not simply located on the roof of the coach but it protrudes from a cavity (called the pantograph recess) which may in itself generate aerodynamic noise whose emission could conceal the pantograph noise. In other cases such as ICE the pantograph is mounted directly on the roof and its noise level is then higher than that of TGV.

4.1.2. *Cavity noise: recess of the pantograph, inter-coach spacing and louvres*

A large number of experimental and theoretical studies have been carried out on cavity grazing flows over a wide range of Mach ($M = U_0/c_0$) and Reynolds numbers, and for a wide range of length/height ratios (l/h); c_0 is the speed of sound.

The different aeroacoustical phenomena which could appear in a cavity are today well known and can be classified as follows:

- for $l/h < 7$–8, the cavity is "open" and in that case, two phenomena can occur:
  - for $l/h > 1$: self-sustained oscillations are created due to the coupling between acoustic waves and shear layer oscillations, often called aeroacoustic feedback;
  - for $l/h < 1$, the cavity is deep and pure acoustic resonances appear.
- for $l/h > 7$–8, the cavity is "closed", the shear layer reattaches on the cavity floor and the acoustic study of the cavity can be treated separately in two steps.

The first step in the aeroacoustic study on the recess of a pantograph or inter-coach spacing is to examine reported results. The recess of the pantograph can be described as a closed cavity and inter-coach spacing as an open and deep cavity.

4.1.2.1. *Recess of the pantograph.* Experiments in wind tunnels can provide information on the flow behaviour of a cavity representing a pantograph recess, compared to normal cavities see for example reference [18]. The main difficulty in using wind tunnel experiments is that the scale of the mock-up has to be sufficient in order to ensure that the geometry and flow characteristics are comparable to real conditions (Reynolds number, thickness and turbulence intensity of boundary layer). Moreover, anechoic wind tunnels are required to investigate acoustic measurements. Figure 5 represents a TGV mock-up ($\frac{1}{7}$ scale) in an anechoic wind tunnel.

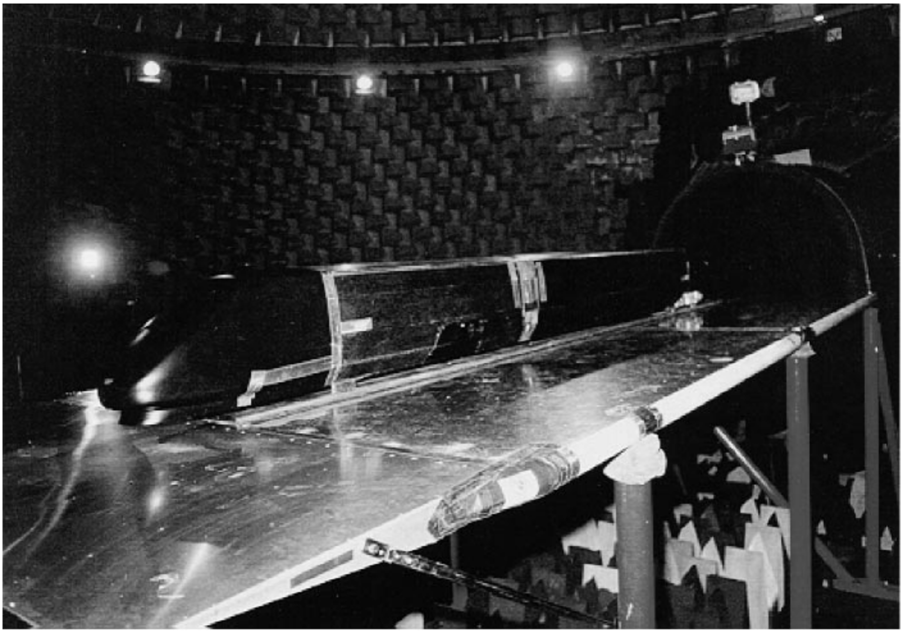

Figure 5. TGV mock up in an anechoic wind tunnel.

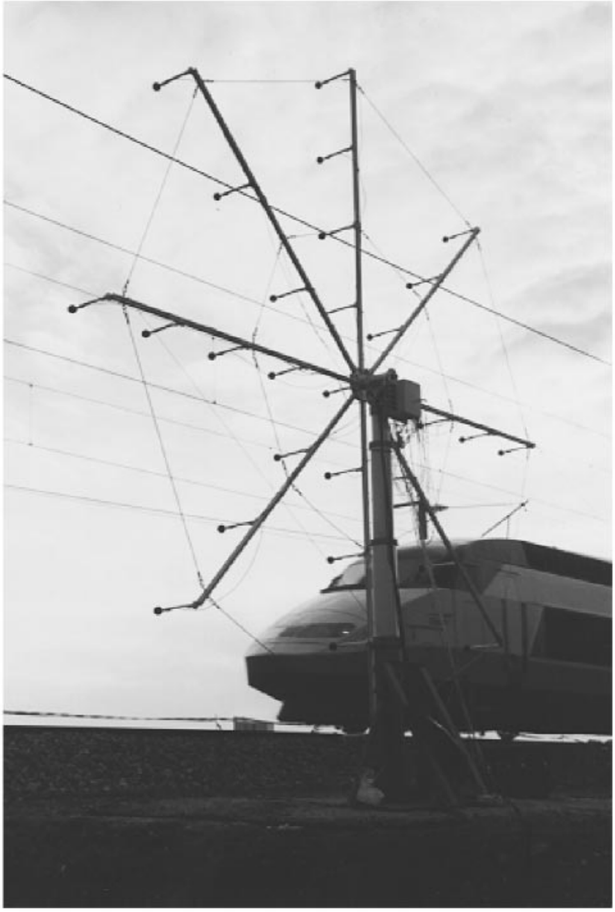

Figure 6. Antenna measurements on line.

All these constraints lead to increasingly complicated and expensive studies and on-line tests may be preferred to eliminate these assumptions. An example of on-line tests with antenna measurements can be seen in Figure 6.

4.1.2.2 *Inter-coach spacing*. The case of inter-coach spacing concerns every train while pantograph recess concerns only trains such as TGV. The best way to identify accurately the unsteady phenomena which occur in the inter-coach spacing and radiate sound, appears to be on-board experiments [19]. The characterization of the influence of these cavities can be obtained by using probes and by comparing the spectra and coherence between the different probes. The identification of these phenomena and the use of anti-turbulence probes can determine whether the phenomena radiate sound.

4.1.2.3. *Louvres*. Louvres can be considered as a series of cavities and can be treated by experiments in anechoic wind tunnels [20,21].

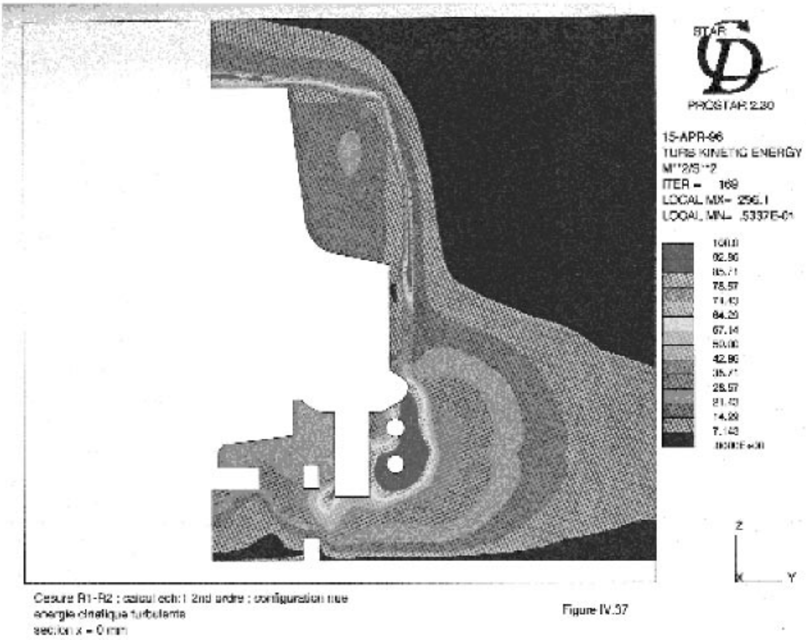

Figure 7. Numerical computations.

4.1.3. *Bogie*

Aeroacoustic sources which can occur in the bogie area are complex. The flow in this part of the train is extremely dynamic with a large number of impacts, flow ejections and recirculating zones. Due to this complexity, it seems necessary to carry out different studies to characterize the aeroacoustic sources of the bogie and its cavity [22]. One way to understand the flow complexity is to carry out numerical simulations with a code for modelling the viscous turbulent flow. One example of such simulation with StarCD (k–ε model, k being the turbulent kinetic energy and ε the dissipation rate) is shown in Figure 7. With regard to the aeroacoustic problem, it must be kept in mind that such computations only provide a steady solution and a statistical idea of turbulence. Nevertheless, provided that the k–ε calculation is reliable, it is possible to identify the turbulence generating areas as steady sources of noise which can be classified according to their turbulence level and their area. Moreover, the behaviour of the flow computed allows a cautious extrapolation of the results to unsteady phenomena of the flow. Finally, probably the main advantage of the numerical study is that all the sections and views necessary to understand the flow can be obtained.

It can be seen that the numerical approach could allow the characterization of a steady source. The objective of experiments carried out in an anechoic wind tunnel was to locate the main sources of noise in the bogie area (shown in Figure 8) and to characterize the unsteady sources. One of the main advantages of a wind tunnel experiment is the ability to carry out parametric studies and to identify the contribution of each part to the global noise level.

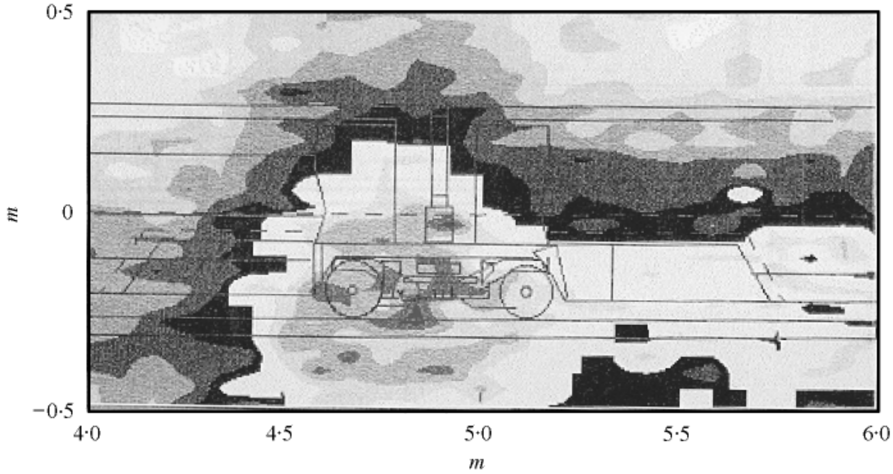

Figure 8. Antenna results in wind tunnel.

The main problem encountered in such an investigation is to determine whether the sources are located inside the bogie or at its border. The wind tunnel experiments are limited due to the complexity of the different sources which are not correlated. The question of similarity of these phenomena between reduced scale wind tunnel and full-scale measurements has to be kept in mind. It can be concluded that the wind tunnel is an interesting tool for characterizing approximately the phenomenon and for studying different principles for control, but it cannot give exact information regarding the bogie areas.

The lack of information from the wind tunnel and the problem of similarity for comparison justify the implementation of direct on-board measurements.

One methodology to characterize the sources on board a real train could consist of using "phenomenological" sensors fixed near to the sources and to put anti-turbulence sensors expected to filter turbulence and to record mainly acoustic waves as shown in Figure 9, representing a TGV experimental set-up. From the calculated correlation between the signal recorded by the phenomenological sensor and the signal received by "anti-turbulence" sensor, it is possible to determine if the source radiates sound, and to construct its spectrum. The main problem of this method is to choose a good phenomenological sensor for which the received signal will be representative of the source, and to locate it near that source. Currently, these types of methods are promising but need to be improved [19].

It can be expected that, once validated with on-line results, both wind tunnel investigations and numerical approaches will offer the opportunity to make parametric studies and to study potential solutions for noise reduction.

4.1.4. *Ventilators*

Another source which could appear around power cars is due to ventilators. If this source is not always easy to suppress, it is at least characterized by specific

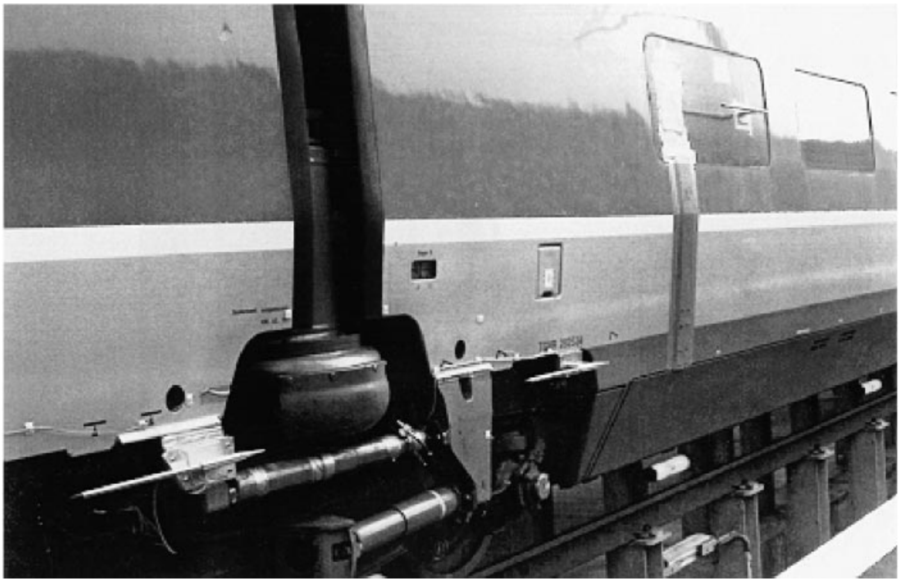

Figure 9. On-line tests.

frequencies and solutions can be found directly by optimizing the ventilators themselves.

4.2. NOISE GENERATED BY TURBULENT FLOWS

4.2.1. *Turbulent boundary layer*: *surfaces*

This source is the lowest aeroacoustic source but it is difficult to suppress because it is due to the development of the turbulent boundary layer on surfaces. Compared to other sources for a high-speed train running at 300 km/h this source is not predominant, but can be significant and even predominant for higher speeds, in, for example, MAGLEV applications.

This source is difficult to characterize due to the wide frequency range and its low level. The turbulent boundary layer could have dipole-like or quadrapole-like radiation pattern. Some "phenomenological" models for turbulent boundary layer sound have been developed [2]. These models are fraught with assumptions and approximations but could lead to a relatively simple equation that can be used as an initial estimate of the wayside noise level generated by the turbulent boundary layer of high-speed trains.

Experimental studies on-line can also give information such as that shown in Figure 10, which gives antenna measurements characterizing the roof of a Transrapid. The analysis of these measurements is not easy [23]. Some sources can be identified near the edges but radiation towards the centreline of the roof presents a confused picture for the identification of turbulent boundary layer sources on the roof.

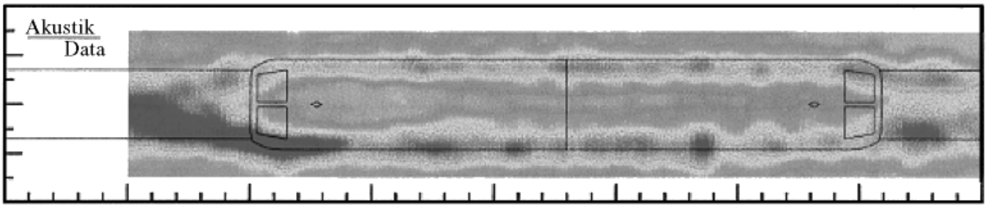

Figure 10. On-line measurements on the roof of a Transrapid.

Figure 11. ICE3.

As stated before, turbulent boundary layer noise is a complex phenomenon which is difficult to suppress. Vehicles sides have never-the-less to be smooth and underfloor equipment needs to be covered. Moreover, turbulent flow over high-speed trains generates fluctuating forces and displacements; this phenomenon could lead to sources additional to those generated when the surface is rigid.

4.2.2. *Boundary layer separation: nose of the power car*

Certain studies such as those on the Shinkansen [12] have shown that the nose of the leading car could be a significant aerodynamic source. This noise is caused by the unsteady air flow induced by the surface shape variations near the leading car nose. By smoothing the front nose surfaces, a reduction of noise of about 10 dB has been obtained on Shinkansen. The design of ICE3 shown in Figure 11 is another example of a solution where flow separation has been eliminated on the leading car. Aeroacoustic optimization of the power-car nose is also important in improving aerodynamic performance and reduce pressure waves generated in tunnels.

4.2.3. *Unsteady wake: rear power car*

The phenomenon of wakes, depending of the nature of the flow (laminar or turbulent) occurs because the flow separates from an obstacle on both sides. Understanding of the wake is very important because it generates increased drag, instability of the dynamic behaviour and is an additional source of noise, even if it is not as important as the other sources of noise. This phenomenon could be characterized by visualizations, aerodynamic and acoustic measurements in a wind tunnel or even by visualization on-line [24].

5. GLOBAL MODELLING OF HIGH-SPEED TRAIN RADIATION

It has been shown that knowledge of aeroacoustic sources of high-speed trains has been improved with specific tools developed for each type of source. When aeroacoustical studies are sufficiently advanced, it will be possible to develop numerical models for every significant source and to design a global noise prediction programme. This kind of model is currently being developed and through parametric studies, will determine the potential reduction of the various sources.

6. DEVELOPMENT OF NEW TOOLS—NUMERICAL SIMULATIONS IN AEROACOUSTICS

As stated in section 4.1.3, numerical simulation tools are currently under development. The first step in the investigation is to analyze turbulent production areas obtained by simulation of Navier-Stokes equations with k–ε turbulence modelling. The main problem of this approach is that it is only possible to characterize the steady source and a direct interpretation of turbulence production areas is usually difficult. Even so, it is possible to use k–ε computation results as a source term implemented in Lighthill equations. The Lighthill analogy method is the most commonly used today but needs a model to be adapted to the geometry (through the Green function). Consequently, this method is only possible for the treatment of simple geometries.

Improvements of computer capabilities could lead, in the near future, to the development of new methods in aeroacoustics based on the computation of the unsteady aerodynamic source term. This aerodynamic computation can be carried out with direct numerical simulation (DNS) or large eddy simulation (LES) codes.

DNS, which deals with all the scales of turbulence, can be used today for simple geometry and limited Reynolds numbers.

LES could be a good alternative. The principle, illustrated in Figure 12, is to separate the different scales of turbulence:

- ○ Large scales of turbulence which produce most of the energy and are thus mostly responsible of noise generation, are explicitly resolved.
- ○ An appropriate model (subgrid scale model) represents the action of turbulence eddies smaller than the size of computational mesh, and must correspond to the dissipative scales.

This method can be associated with a Lighthill analogy or a method based for example on the resolution of Euler's equations for the acoustic propagation and seems to be the most promising in the near future to treat industrial applications.

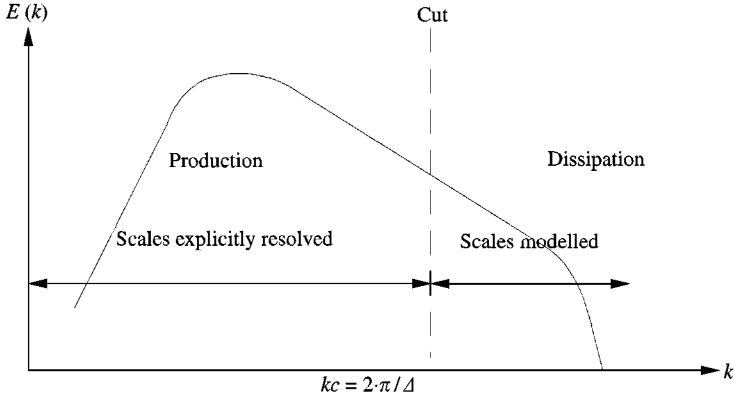

Figure 12. Turbulence spectrum.

7. CONCLUSION

It has been shown in this paper that the first step of acoustic studies is to identify the various sources. A good understanding of the source and its characterization is necessary to find a good solution. In order to study the different sources the most suitable tool has to be chosen to represent the physical characteristics. These tools could be theoretical, experimental, in wind tunnel or on-line, and in the future based more and more on numerical simulation.

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