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THE VALIDITY OF RECIPROCAL ACOUSTIC TRANSFER FUNCTION MEASUREMENTS ON TRUCKS FOR PASS-BY NOISE

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1. INTRODUCTION

Reciprocity is a well and long known principle in acoustics. Its principle has been researched and applications have been described in many fields. Within the European research project "PIANO", extensive use is made of acoustic reciprocity.

Acoustic transfer functions between volume velocity of a patch on the surface of an engine, or other noise source, and the sound pressure at some distance are used to study:

- The contributions of surface patches to pass-by noise
- The effectiveness of encapsulations, absorption, etc on the truck
- The influence of road surface reflection on the pass-by noise

The main advantage of applying reciprocity is the practicality of the measurements :

- Normally one is interested in the relation between many source positions and a limited number of positions for the sound pressure.
- Loudspeakers and other artificial sound sources are normally far larger than microphones, which means that for direct measurements they have to be build into the original radiating structure (expensive) or their supplementary presence on the radiating structure will distort the diffraction (inaccurate).

The issues of investigation were :
- Instrumentation possibilities
- Vehicle conditioning during measurements
- Air flow and air temperature effects on the accuracy
- Repeatability in practical conditions

2. DEFINITIONS AND PRINCIPLE

The basic interest is in the relation between the motion of the structure surface (engine, components, etc.) or the air motion at openings (nozzles, apertures) and the sound pressure at some distance. In varioous ways this is simplified to the relation between the volume velocity of an omnidirectional monopole source and the sound pressure at an omnidirectional monopole receiver.(Ref. 1,2,3)

(1) $$H_{ir}^{AA} = \frac{P_r}{Q_i}\Big/ Q_{r=0} \qquad (\mathrm{Ns/m^5})$$

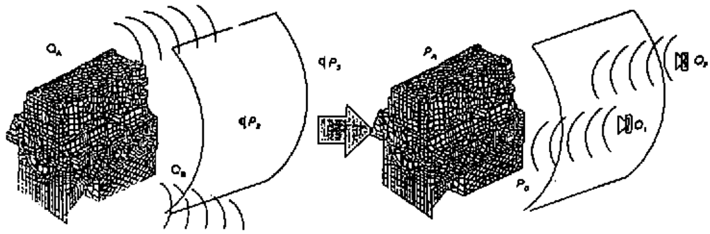


Fig.1 : Direct and reciprocal experiments.

The basic relation for an acoustic two port system, used to derive reciprocity relations :

(2) $$P_1^0\, Q_1^* \;+\; P_2^0\, Q_2^* \;=\; P_1^*\, Q_1^0 \;+\; P_2^* + Q_2^0 \qquad (4)$$

In the direct experiment the volume velocity at port 2, Q_2^0, is zero. In the reciprocal experiment the volume velocity at port 1, Q_1^*, is zero, which reduces relation (2) to :

(3) $$\frac{P_2^0}{Q_1^0}\Big/ Q_{2=0}^0 = \frac{P_1^*}{Q_2^*}\Big/ Q_{1=0}^* \qquad (\mathrm{Ns/m^5})$$

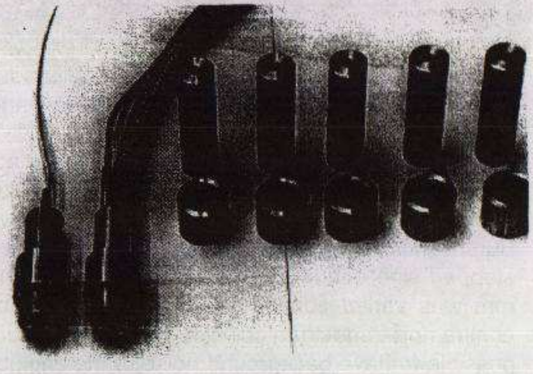
In other words, in the reciprocal measurement a point source can be placed at the receiver location and the pressure is taken on the surface of the original sound source.

3. INSTRUMENTATION

For the experiments different calibrated volume velocity sources and normal instrumentation microphones were used. The most accurate measurements were possible using a tube sound source after a principle by Verheij (Ref.4).

Figure 2 shows the implementation used for the reciprocity validation. Both the source and the microphones have nearly identical diffraction, due to a nearly identical geometry. The diameter of 22 mm ensures omnidirectionality and the pressure inside the nozzle gives an accurate and stable signal for the volume velocity. The source calibration is also largely independent of the acoustic boundary conditions.

Fig. 2 : Photo of a tube sound source (centre lying) and microphone holds with and without microphone.



4. CONDITIONS ON THE VEHICLE

The main factors that determine the acoustic transfer functions are vehicle component diffraction and road surface reflection.
This is easily imitated during a stationary transfer function measurement. The acoustics are not affected by motion and the vehicle position relative to the microphone during passage is well known.

Still one can expect some deviations:

- The relative positions of the components of the vehicle and component height relative to the road differ up to 0.04 m between the stationary vehicle and the accelerating pass-by test.
- The temperature of the air on a moving truck will vary locally near hot components up to 30% of the absolute temperature. This means that the source impedance and the propagation speed of waves in the air are potentially seriously affected
- Air flow during ISOR362 pass-by test can reach up to 5% of the propagation speed of waves in the air. The air flow could impair the validity of the reciprocity

5. EXPERIMENT SET-UP

For the investigation measurements were performed on a small size IVECO truck placed in the CRF semi-anechoic measurement chamber in Turin Italy. The chamber allows stationary and running measurements on a chassis-dynamometer (Fig. 3)

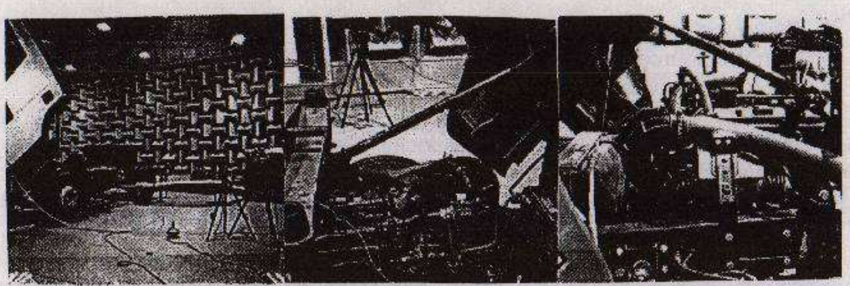


Fig. 3 : Test situation, vehicle, engine and sound sources.

The tube source was placed on the engine surface at different locations and the microphone was placed at different positions, 3.5 m from the truck. During the reciprocal measurements this was inversed.
Burst random excitation was used for the stationary measurements and stepped sine during the measurements with running engine. The engine rpm was varied continuously to prevent that order components in the engine noise spectrum coincide with the sine frequency. In this way it was possible to have background noise of the engine of the same level of the sound source during the FRF measurement.

6. RESULTS

The first verification of the reciprocity, under nearly ideal conditions shows nearly perfect reciprocity, within +-1dB. (Fig 4).

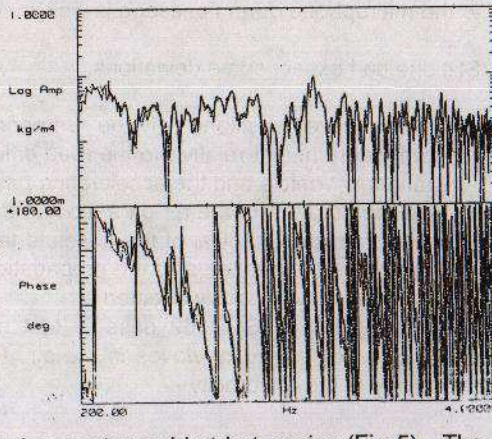


Fig. 4 : Direct (solid) and reciprocal (dashed) acoustic transfer function

This experiment was repeated on a stopped but hot engine.(Fig 5). The maxima in the FRF move up in frequency by approximately 2 % in warm condition. The resulting amplitude difference is around 1 dB, the phase shift depends strongly on the frequency (from 10 to 180 degrees).

The air flow was not simulated on its own, but only measured with the engine running.(Fig.6). This meant that a number of effects are combined :

- External air flow due to cooling air in the chamber.
- Flow around the engine due to partial action of the engine cooling fan.
- Temperature changes near the engine and in the entire chamber.
- Slight position changes of the driveline due to load variation.

The reciprocal measurement on a stopped cold engine compared to the running measurements show shifts in amplitude and phase; ± 3 dB at the peaks. A systematic increase or decrease of amplitude is not observed, which means that the difference will reduce significantly if the acoustic transfer functions are used on a third-octave band level.

Some more experiments were performed to asses the influence of positioning, related to repeatability and component positioning. Figure 5 shows a +-3 dB effect of a microphone repositioning on the engine by 0.02 m

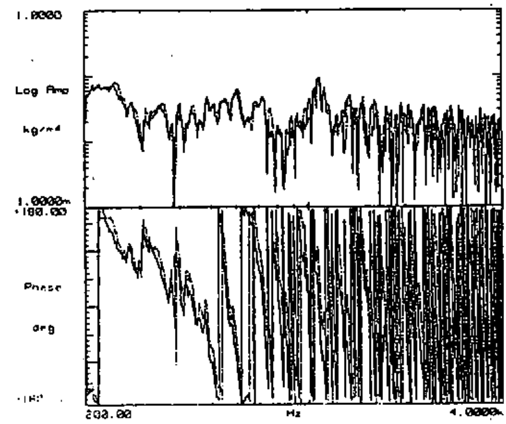


Fig. 5 : Direct acoustic transfer function measurements. In normal condition (solid) and on the hot engine just after the engine stopped (dashed)

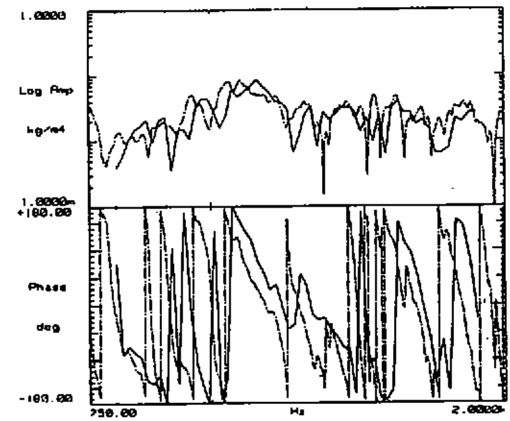


Fig. 6 : Direct measurement running engine (solid) and cold stationary reciprocal measurement (dashed)

7. CONCLUSIONS

- The reciprocity of the sound field around a truck is perfect.
- The available instrumentation is adequate. It was possible to perform accurate reciprocity validations, even minimal (1 dB) shifts in response could be measured.
- Temperature and flow effect have shown measurable deviations under well controlled conditions. But for any practical application these deviations are within the positioning/calibration/measurement accuracy for third octave band data.
- Source/sensor and vehicle component positioning is critical for individual point to point acoustic transfer functions. But in practice, trucks tend to move during pass-by test and the average acoustic transfer over passage intervals of one or two meters are not influenced by 0.02m source position shifts during stationary reciprocal measurements;
- Reciprocity can therefore, without reservation, be used to study pass-by noise of vehicles.

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