THE USE OF VOLUME VELOCITY SOURCE IN

TRANSFER MEASUREMENTS

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Abstract

In the automotive industry there is a growing need for measurement of acoustical transfer functions in connection with transfer path analysis, the main outcome being acoustical source contribution analysis. These transfer functions are from monopole Volume Velocity at a source location to the resulting sound pressure at a receiver (listener) position. In most cases it is an advantage to make use of reciprocity, which allows the monopole source position and the pressure response position to be interchanged. The source to be used for these measurements must be powerful and omni-directional, and the frequency range of interest is typically 50-6300 Hz. So the Brüel & Kjær OmniSource™ Type 4295 is in many ways perfectly suited for the application. This paper will discuss the design criteria for a Volume Velocity Source as well as the verification of the performance. Also the use of Volume Velocity Source in Transfer Path Analysis often called Source Path Contribution is described. Practical examples using the Volume Velocity Source will be shown.

Design of the Volume Velocity (VV) Source

The Brüel & Kjær OmniSource™ Type 4295 (see figure 2) has been designed to provide a high level (Lw = 105dB ref. 1pW) of omni-directional sound radiation over a broad frequency range from around 60 Hz to 6.3 kHz. The target application was room acoustics measurements. So the OmniSource is in many ways perfectly suited for the Volume Velocity application. The only feature missing is a capability to measure the Volume Velocity output and – in particular – the transfer function from Volume Velocity output to the (pressure) response at a set of positions. Figure 1 shows a new Volume Velocity measurement adaptor to be fitted on the Type 4295 OmniSource™. Notice the ¼" intensity microphone pair Type 4178 built into the adaptor. The cylindrical tube section with a diameter of 4 cm will suppress all non-planar waves at the microphones up to approximately 5 kHz. The first higher order mode has a single radial node line and it can propagate above 5 kHz. But by measuring the pressure on the tube axis, this mode should in principle not be detected, which fits with the fact that it does not contribute to the output Volume Velocity. The first higher order mode, which has non-zero pressure on the axis, can propagate only above 10.4 kHz. At 6 kHz this mode will be attenuated 41 dB over the 3 cm from the opening to the outermost microphone B. So if the two microphones – A and B – could measure the undisturbed pressure exactly on the axis, then only the propagating plane waves would contribute significantly to the measurement over the considered frequency range. In practice, the microphones will disturb the sound field and not measure the pressure exactly on the axis.

Assuming that only plane waves are measured, the plane wave components propagating in the two directions can be estimated from the two microphone signals. These two plane wave components can be extrapolated to the opening of the tube, and the Volume Velocity output can be calculated.

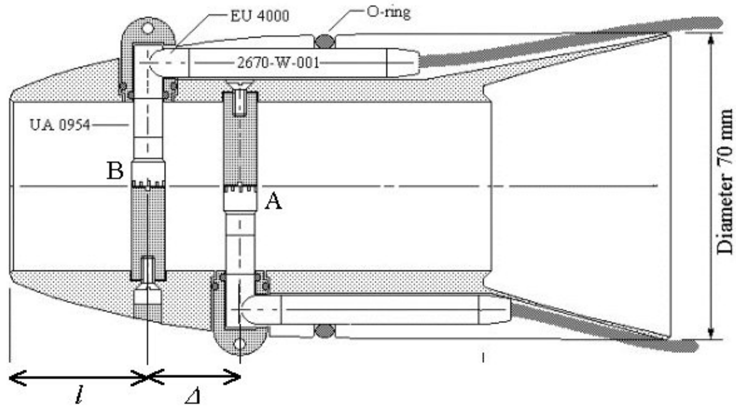

Figure 1*: Volume Velocity measurement adaptor for OmniSource™ Type 4295*

We measure the pressure at the two microphones: p_A and p_B. Beyond that we measure the response at a position R. From these signals we average the Cross spectral matrix:

	A	B	R
A	C_{AA}	C_{AB}	C_{AR}
B		C_{BB}	C_{BR}
R			C_{RR}

We use the following notation

S	Cross-section area of the tube.
l	See the Figure 1. Typically it is 3 cm.
Δ	See the Figure 1. Typically it is 2 cm.
k	Wave number (2π*f*/*c*)
ρ	Density of the air
c	Propagation speed of sound

The Auto-spectrum C_{QQ} of the Volume Velocity in the opening of the adaptor and the Cross spectrum between the Volume Velocity and the Response signal can then be shown to be:

$$C_{QQ} = \left(\frac{S}{\rho c}\right)^2 \frac{C_{AA}\cos^2(kl) + C_{BB}\cos^2(k(l+\Delta)) - 2\mathrm{Re}\{C_{AB}\}\cos(kl)\cos(k(l+\Delta))}{\sin^2(k\Delta)} \quad (1)$$

$$C_{QR} = \frac{S}{\rho c}\frac{C_{AR}\cos(kl) - C_{BR}\cos(k(l+\Delta))}{j\sin(k\Delta)} \quad (2)$$

Using these two spectra, the Frequency Response Function H_{QR} between this Volume Velocity and the Response signal can be obtained as:

$$H_{QR} = \frac{C_{QR}}{C_{QQ}} \quad (3)$$

Verification measurements in an anechoic chamber

Figure 2: *Picture showing the OmniSource™ with VV adaptor above a turntable*

The performance of the Volume Velocity (VV) source was checked in Brüel & Kjær´s anechoic chamber. For this a Portable PULSE™ Type 3560C with a 3109 Input/Output module was used together with a Power Amplifier Type 2716 and a single Array Microphone Type 4935 to measure the Response pressure. The OmniSource™ Type 4295 with a VV adaptor was mounted horizontally approximately 1.2 meter above a Turntable in such a way that it could be rotated around a vertical line through the output aperture - see Figure 2 below.

The formulae for calculation of the Volume Velocity Auto-spectrum C_{QQ} and the Volume Velocity to Response transfer function H_{QR} were first programmed in PULSE Language, later they were implemented as External Functions. Also, the two phase-matched microphones A and B of the VV adaptor were precisely calibrated using a Sound Intensity calibrator Type 3541.

Measurement of maximum SPL output

Figure 3 shows the 1/3-octave SPL spectrum measured exactly 10 cm in front of the aperture of the VV adaptor, when the Type 4295 OmniSource™ is driven approximately to its maximum output with Pink noise, the excitation was frequency band limited to the interval 0-6300 Hz. Figure 4 show the 400 line FFT spectrum at 10 cm distance when the Type 4295 OmniSource™ is driven approximately to its maximum output with White noise. Notice that loudspeaker distortion is not critical, because we only deal with the radiated sound field – specifically with a transfer function in that sound field. As seen the VV source has a reasonable flat output as a function of frequency.

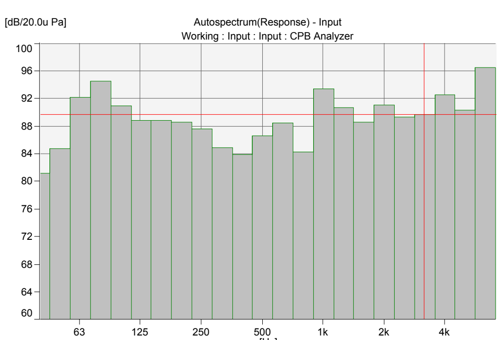

Figure 3: *1/3-octave SPL spectrum at 10 cm distance with maximum **pink** noise excitation*

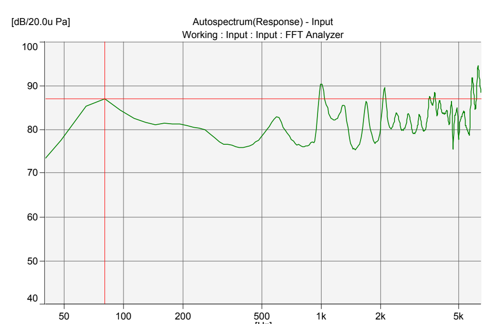

Figure 4*: FFT based SPL spectrum at 10 cm distance with maximum **white** noise excitation*

Measurement of directivity.

At 2 meter distance from the output aperture of the VV adaptor the 1/3-octave SPL spectrum was measured as a function of the off-axis angle with 10° intervals between the measurement points. Figure 5 shows sequence of plots of the radiation patterns for the 1/3-octave bands 500, 1000, 2000, 2500, 3150 and 4000Hz. Up to around

3 kHz the SPL does not change more than 5-6 dB over the 360° angle interval. At higher frequencies (not shown here) the variation over angle goes up to approximately 15 dB.

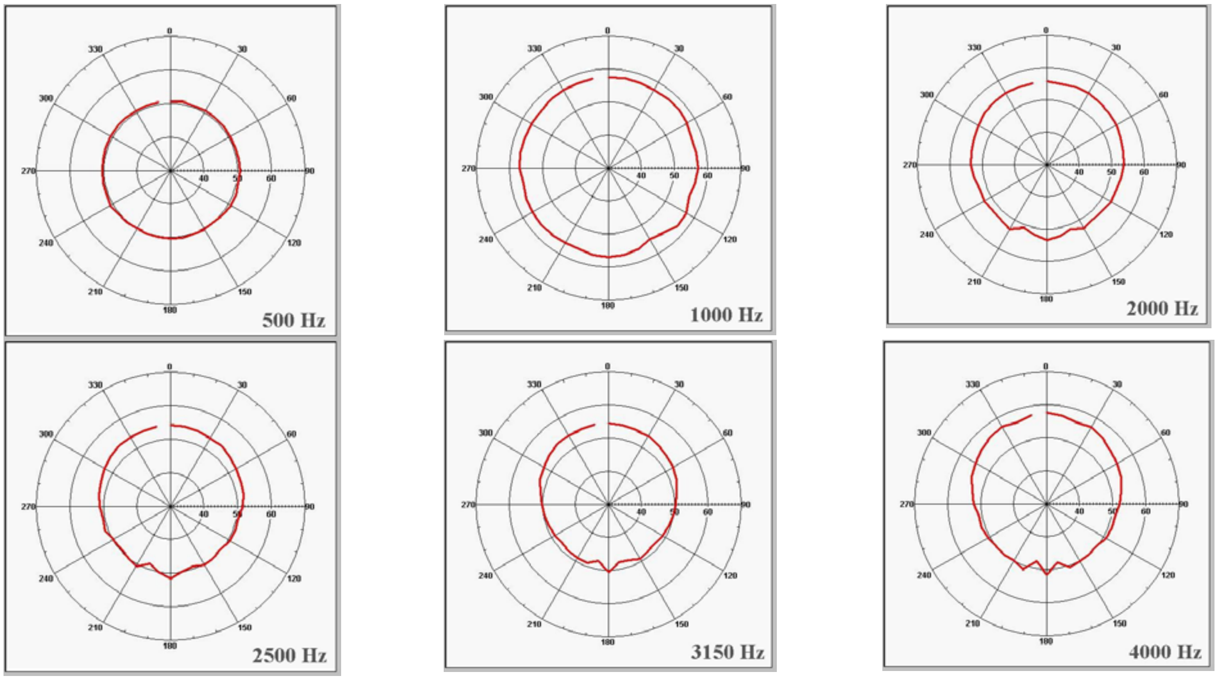

Figure 5: *Directivity patterns from 500Hz to 4kHz*

Check of the Transfer Function Measurement

The main application of the Volume Velocity source is measurement of the Frequency Response Function H_{QR} between this Volume Velocity output and a Response signal. If the VV source radiated as an ideal monopole point source, then the frequency response function should be given by the following expression:

$$\hat{H}_{QR} = j\rho ck \frac{e^{-jkR}}{4\pi R} \quad \text{Ideal Monopole Point Source} \quad (4)$$

So we can compare our measurements with this expression, see Figure 6. At low frequencies the VV source is highly omni-directional, so the agreement is expected to be good. At higher frequencies, the measured transfer function H_{QR} will tend to deviate from the ideal function $\hat{H}_{QR}$ in the same way as the radiated pressure deviates from the omni-directional pressure distribution of an ideal monopole. Because the VV source concentrates the radiation in the axial direction at high frequencies, the response H_{QR} measured on the axis is expected to be larger than the ideal omni-directional $\hat{H}_{QR}$. Looking at the phase (not shown here), the agreement is best, if the ideal monopole is assumed to be 1.2cm in front of the aperture, i.e. the acoustic center is located 1.2cm, in front of the aperture.

A few comments on the deviations between the ideal omni-directional transfer function $\hat{H}_{QR}$ and measured transfer function H_{QR}:

- At 10 cm distance the measured H_{QR} is very smooth and agrees very well with the omni-directional $\hat{H}_{QR}$, the only deviation being the high-frequency lift due to the directivity of the source in the direction of the measurement position. This good agreement shows that the VV adaptor is working very well.
- At larger distances the influence of the environment will introduce further differences between H_{QR} and $\hat{H}_{QR}$. The ability to measure these differences is the main benefit of the VV source.
- The influence of the environment (the OmniSource™, its support structure, the measurement equipment, the floor and the room in general) is seen to be increasing from 10 cm to 1m and again from 1 m to 2 m distance. At the chosen microphone position the response is mostly decreasing, and ripples are showing up.

- In the low/medium frequency areas, these ripples (and the shape of the measured response function in general) are seen to remain almost constant during the rotation of the source around the aperture. This indicates that the deviations (the ripples) are not due to parts rotating together with the VV source – they must be created mostly by the surroundings.

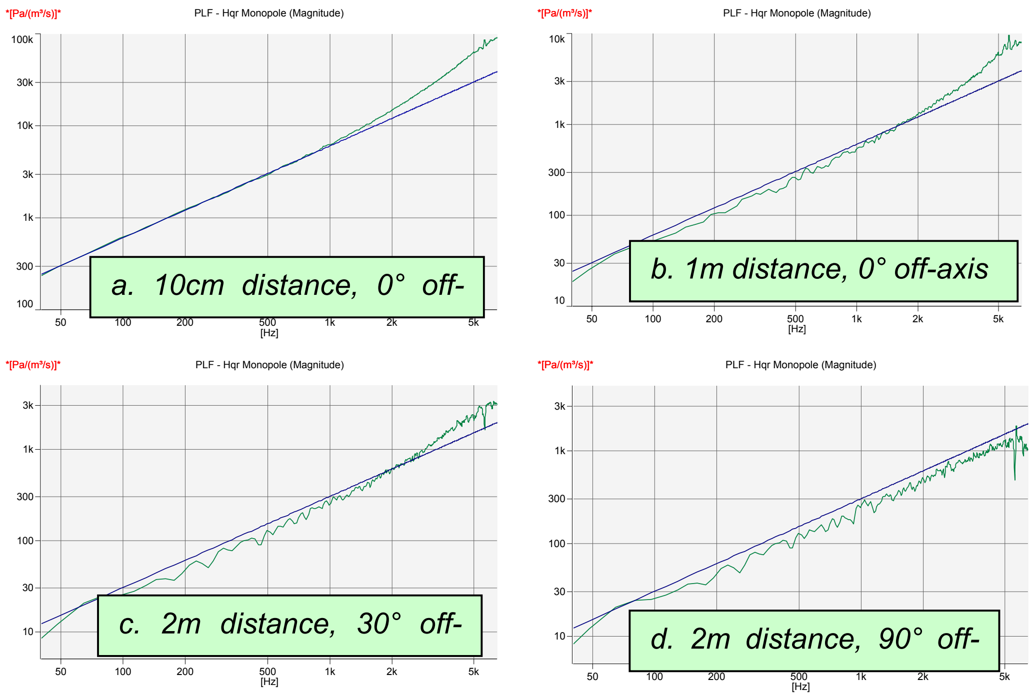

Figure 6: *Ideal (blue) and measured (green) transfer function* H_{QR} *for a response position on and off-axis at various distances from the aperture plane.*

The Frequency Response Function H_{QR} of Figure 6a - measured at 10 cm distance (upper left) - has some ripples around 5.5 kHz. These ripples are probably associated with corresponding ripples in the phase of the cross spectrum between microphones A and B – (not shown here). Probably the phase ripple is caused by the interaction of the sound field in the tube with the two microphones and their extensions across the tube. This is a small problem to be addressed in the future.

Measurement Example

Some measurements were carried out on a Volvo60 passenger car using the VV source, see Figure 7, the intentions was to measure the transfer paths for both airborne noise as well as structure borne noise. This series of measurements were unfortunately not finished, when this paper was written, so only an example is shown here. The VV source was placed in the drivers seat (right hand steering wheel car), a ½" microphone Type 4190 was placed under the oil sump and an accelerometer was placed on the right front wheel suspension.

Measurement were performed using both FFT (Fast Fourier Transform) as well as SSR (Steady State Response) techniques. For the FFT techniques 400, 1600 and 6400 lines were used in order to see the influence of resolution and both Random Signal (with Hanning Weighting) as well as Pseudo Random Signal (with Uniform Weighting) was used in order to see the influence of excitation signals. SSR technique uses stepped sine excitation, here the step frequency interval was chosen so it corresponded to the 400 line FFT resolution.

Figure 8 shows some measurement results. The functions used were the following: Autospectra, Coherence, Cross-correlation, Volume Velocity and Frequency Response Function (Volume Velocity to Pressure) and for SSR also Measurement Time and Standard deviations as a function of frequency were displayed. Autospectra of the two microphone positions A & B in the adaptor should not differ too much (Figure 8a). Coherence between the between microphone B and the response position, R should not be too low due to background noise.

Figure 7: *VV source in a Volvo60 passenger car*

Cross-correlation was used to identify the major time delays between excitation point (microphone B was used) and the response point, R at he oil sump (Figure 8b), Major delays at 6, 14 and 21ms. The spectrum of the Volume Velocity output (inverse proportional to frequency) was used to verify there was not too much acoustical influence from the surroundings, i.e. lack of free field (Figure 8c). Finally the Volume Velocity Spectrum was calculated (Figure 8d).

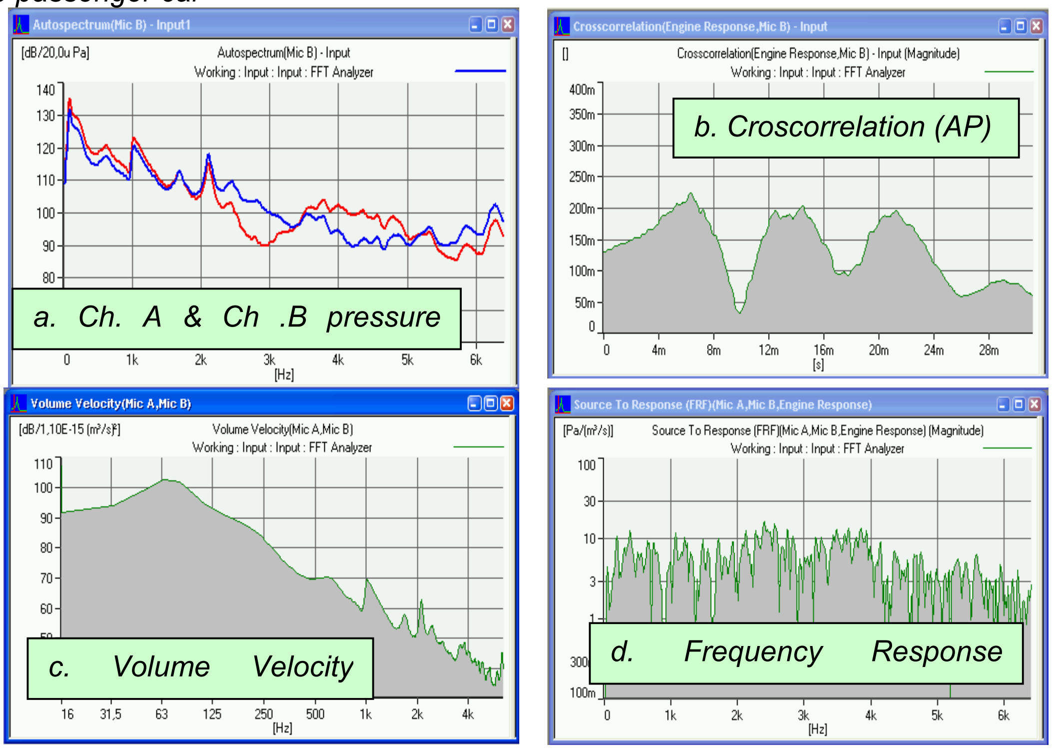

Figure 8: *Measurement results from a Volvo60 passenger car*

Conclusion

In this paper we have introduced the design and use of a Volume Velocity Source based on a powerful OmniSource™ Type 4295 fitted with an adaptor, which includes a pair of phase-matched microphones in order to measure the VV-output as well as the VV to pressure Frequency Response Functions.