Measurement of linear and nonlinear loudspeaker parameters using high speed cameras and 3D vision methods

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Abstract: 3D vision methods are a powerful tool for measuring full-field vibration patterns of sound sources. In this paper, these methods are applied to the measurement of low-frequency loudspeakers parameters. A stereovision setup with at least one high-speed camera is used to record the movement of the membrane. Then, using Digital Image Correlation (DIC), the displacement of the membrane is extrapolated. This quantity, coupled with electrical measurements at the loudspeaker terminals and pressure measurement, is used to calculate linear (Thiele and Small data) and non-linear (dependence of the Bl factor and suspension compliance on the displacement) parameters. As this method can also provide full-field vibration data, the rocking mode behaviour of the membrane is also investigated. Finally, the pros and cons of the proposed method will be discussed and also tested by measuring displacements of a loudspeaker's membrane without previous preparation.

Keywords: loudspeaker measurement, 3D vision, high-speed cameras

0 INTRODUCTION

Thiele and Small parameters are widely used by loudspeaker manufacturers for predicting the frequency response of sound systems. In the last decades, there has been significant progress in methods for measuring these parameters. A very popular method consists in measuring the electrical impedance of a speaker under two different test conditions, for instance with or without added mass [1] or by using a box of known volume [2]. A laser velocity sensor can also be used to perform the measurement without the need of added mass or known acoustic compliance [3,4]. Standardized

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methods can also be found in Ref. [5].

Modern methods of measuring driver parameters generally include a laser (with triangulation or Doppler techniques). The development of 3D vision methods allows considering an alternative to lasers for measuring the membrane displacement. Thus, cameras can be used to simultaneously measure the displacement of several points of the same object and could save measurement time.

After the introduction of ultra-fast cameras on the market, 3D vision methods have been applied to vibration measurement. A review has recently been proposed by Baqersad et al. [6]. One of the most popular setups uses two cameras to record two movies from two different points of view. For each time frame, a pair of images taken from both cameras is used to calculate the 3D coordinates of the parts of interest on the measured object using digital image correlation algorithms (SDIC) or target tracking. However, as high-speed cameras are expensive and may be difficult to synchronize, alternative setups have then been proposed. For instance, a four mirrors setup can be used to build a single camera pseudo-stereo system [7] for which the two points of view are recorded on the two halves of a camera sensor. This setup was used to measure the vibrations of a planar plate driven by a shaker using SDIC [8] or target tracking [9] or a loudspeaker membrane [10]. As the four-mirror system can be difficult to adjust precisely, a two-mirror system has been used to measure mode shapes of a loudspeaker membrane [10]. The previous systems allow measuring the components of the movement according to the three directions of space. However, in some cases, it may be sufficient to know the contribution along only one axis. For example, when attempting to calculate the field radiated by a vibrating structure using the Rayleigh integral, only the velocity normal to the structure is required. In this case, a setup with a single high-speed camera and without mirror can be used to measure the out of plane vibration of an object [11,12].

The technique proposed in this document was first presented in Ref.[11], it is here supplemented by new results. Thus, the measurement of the Bl factor is more accurately achieved thanks to the excitation carried out using another loudspeaker. Data on the position dependence of the compliance are also added. Measurement of the membrane displacement using visible features on the membrane is also reported. This avoids applying a speckle drawing on the loudspeaker and do not damage the tested loudspeaker.

This proceeding is organized as follows: Section 1 describes the theoretical background of the proposed method. Section 2 reports measurement results for two speakers. Results obtained using the vision method are compared to the ones measured with a Klippel R&D analyzer system. Finally, results are discussed and pros and cons if the methods are listed.

1 3D vision theory

The 3D shape of samples is obtained by processing multiple point-of-view images of them. The involved cameras must have known sensor sizes, focus length, position, and orientation in order to triangulate the 3D location of a set of measurement points defined over the sample. The triangulation process is based on the pinhole camera model, in which an operator K projects any 3D location $(X,Y,Z)^T$ onto a pixel matrix of the camera noted as $(u,v)^T$, according to $(uZ,vZ,Z)^T = K\ (X,Y,Z)^T$. Note that the 3D coordinate system is defined by the orientation of the camera sensor. The operator K is assembled as

$$K = \begin{bmatrix} f_u & 0 & p_u \\ 0 & f_v & p_v \\ 0 & 0 & 1 \end{bmatrix}, \tag{1}$$

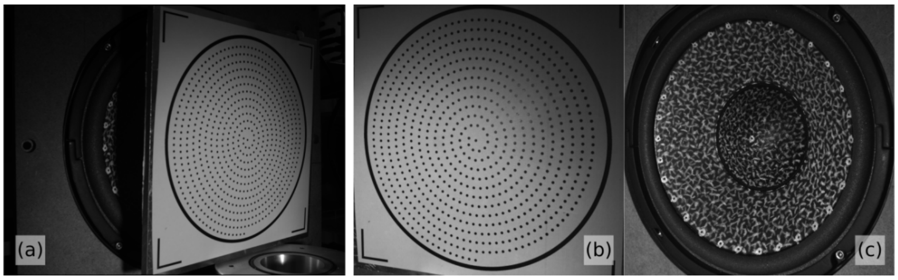

Figure 1: Images for extrinsic calibration: (a) left point of view picture with calibration target; right point of view taken with Photron SA-X2, (b) calibration target, and (c) speaker at rest.

and it contains information about the focal lengths along the u and v axes, and also about the optical center of the objective of the camera in image coordinates (p_u, p_v). A set of distortion coefficients completes the intrinsic parameters of the camera.

The projection operation allows different points in space to end up at a single point in the image and different values of Z. This solution set is defined by the line going through the camera center and the point in the image. Therefore, a single camera view is not sufficient to describe the 3D location of objects by using this model. However, if a second camera viewing at the same object is considered, two image points corresponding to the same point $(X, Y, Z)^T$ will define two 3D lines that allow triangulating the 3D location at the object.

When using two or more cameras, each one defines a 3D coordinate system related to the world coordinates by the rotation given by R_i (3x3) and the translation T_i (3x1). Using this extrinsic parameters, and being k_i the distance between the point $(X, Y, Z)^T$ to the camera center, the projection operation becomes $(k_i u_i, k_i v_i, k_i)^T = K_i R_i (X, Y, Z)^T + T_i$. Therefore, the triangulation method of two corresponding points (u_1, v_1) and (u_2, v_2) remaps the point in the first camera to the line $(X_1,\ Y_1, Z_1)^T = R_1^{-1} K_1^{-1} k_1 (u_1, v_1, 1)^T - T_1$, with varying k_1. The projection of this line to the image plane in camera 2 generates an epipolar line. The value of k_1 that minimizes the distance between the epipolar line and (u_2, v_2) is input into the line $(X_1,\ Y_1, Z_1)^T$ to triangulate the point in world coordinates.

For each setup, the intrinsic and extrinsic parameters need to be retrieved by a calibration process using several images of a flat calibration target. The target is presented to each camera at different positions for the intrinsic calibration. And subsequently, when the setup is well aligned, the target is shown to the cameras at different positions for the estimation of the extrinsic parameters. Fig. 1(a) and (b) correspond to a single target position viewed from the two points of view using different cameras (a: left, b: right). Fig. 1(c) shows the loudspeaker at rest viewed from the camera placed at the right side. The detection of the points in the targets is improved by using Gaussian intensity points and dual conic detection in edge images [13]. The calibration optimization procedure is performed using standard OpenCV functionalities [14].

In this work, a setup with a single high-speed camera and without mirrors is used to measure the out of plane vibration on loudspeakers. We note that the design of loudspeakers highly privilege out-of-plane, i.e. normal, displacements on the membrane. The initial shape of the membrane at rest is found by a conventional 3D vision system. A second camera is used to take a single photograph at the beginning of the measurement. Then, a line normal to the initial shape is associated to a virtual camera for the triangulation procedure of subsequent frames instead of requiring a real epipolar line coming from a second camera device. Thus, the sub-pixel tracking of a conveniently chosen set of measurement points over the sequence of images gives accurate out-of-plane displacement values, especially if the camera is placed at an angle increasing the visibility of the displacements [9].

The measurement of the initial shape requires to find corresponding points between two point-of-view images by a correlation procedure using features or texture in the membrane. Usually, one must draw or stick a pattern to the sample in order to ease an accurate impairment of the points. Also, the tracking of measurement points using correlation over the neighboring area is benefited by those patterns. However, this kind of intervention on the loudspeaker can modify the mechanics of the membrane and may also be considered as destructive if the technique is intended for inline quality control. Therefore, a technique that dispense with this intrusion is desired. So, an unspoiled loudspeaker, without drawings or artificial pattern, is considered for the measurement. In this work, we manually select three points on one initial state image along the inner circle defined by the dome of the loudspeaker at rest. After these points are selected, we use the assistance of their epipolar lines to select their corresponding points into the second point-of-view image. The 3D location of the inner circle is triangulated and sampled to obtain a set of measurement points. This way, the normal direction required by the single-axis vision technique is determined by this set of points known to be at the same depth position over the membrane. The 2D tracking of these points takes advantage of the features provided by the shape and texture of the membrane, and the illumination conditions. Finally, the out-of-plane displacements are triangulated.

2 Measurement results

The single-axis vision method is used in this work to measure linear and nonlinear parameters that characterize a loudspeaker (woofer AB Sound TW1041) with white drawings on the membrane. The displacement of the membrane is measured using a professional high-speed camera Photron SA-X2, and a single point measurement is also performed with a compact laser vibrometer Polytec CLV-2534. The linear Thiele and Small parameters are obtained by fixing the loudspeaker on a mechanical isolation breadboard towards the setup comprising the camera viewing at an angle of approximately 40°, an illuminating LED spot, and a laser vibrometer head. The speaker is excited by a logarithmic chirp signal (20 Hz to 1 kHz over 2 seconds, 1 V peak). The voltage at the terminals of the woofer and the electrical current going through a 0.940 Ω resistance connected in series are measured simultaneously. The frame rate of the camera is set to 4,000 fps with exposure time 0.2 ms and resolution of 1024 x 1024 pixels. Electrical and vision measurements should be performed simultaneously, but here they are synchronized by a signal processing technique. The continuous wavelet transform (CWT) with complex Morlet wavelet function is applied to the signals: voltage $U(t)$, current $I(t)$, and displacement at a particular point $x(\mathrm{t})$. The ridge of the CWT coefficients has information about the instantaneous frequency f, phase, and amplitude of the signal at each sample [15]. The impedance curve $Z(f) = \mathrm{U}(f)/I(f)$ and Frequency Response Function (FRF) $x(f)/U(f)$ are then simply obtained. Fig. 2 shows the measured electrical impedance curves and the estimated impedance using the model from Ref. [4].

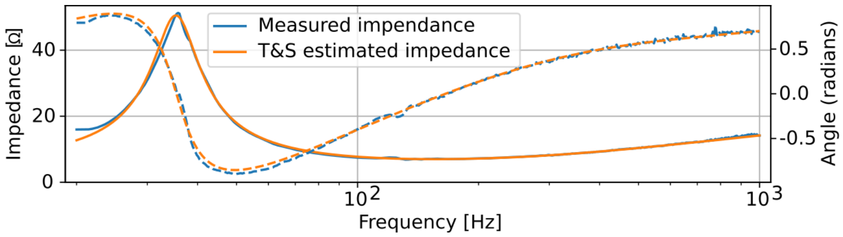

Figure 2: Electrical impedance of the woofer. Magnitude in plain line, dashed line for phase.

The recovered amplitude of displacement using the laser vibrometer and different measurement points of the vision method are shown in Fig. 3. There is a high agreement between the curves from low frequencies up to 200 Hz, but it is possible to notice the variations in response at higher frequencies depending on the location over the membrane. These responses allow us to complete the Thiele and Small estimation of linear parameters. The obtained results are similar to the measurement of the same loudspeaker using a Klippel Distortion Analyzer (in parenthesis), e.g. : Force factor $Bl = 9.72(9.69)$ T.m, moving mass $M_{ms} = 36.8(31.4)$ g, mechanical resistance $\mathrm{R}_{ms} = 2.14(1.92)$ kg/s and suspension compliance $C_{ms} = 1/K_{ms} = 0.55(0.52)$ mm /N.

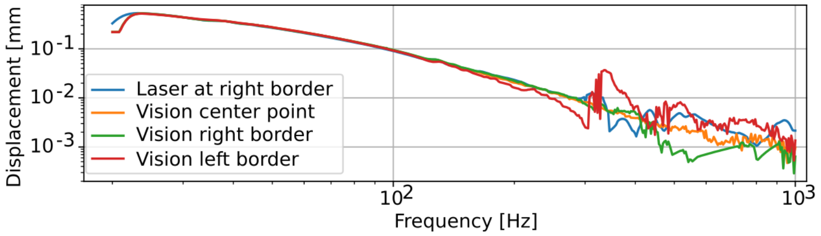

Figure 3: Displacement as function of frequency at different locations.

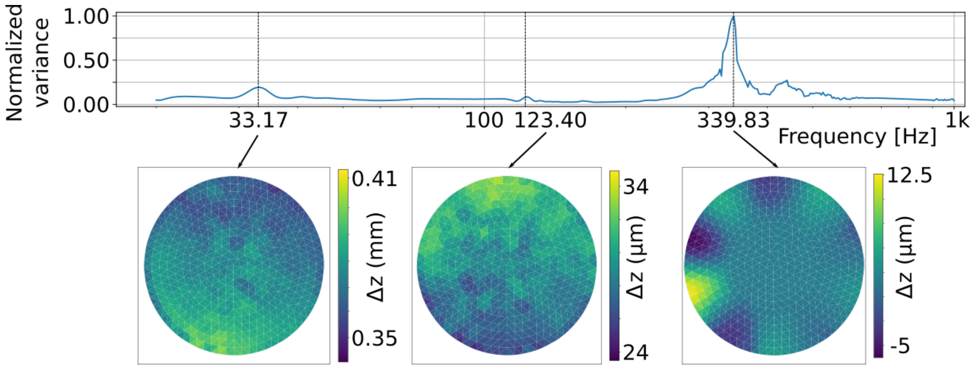

Figure 4: Variance based indicator of non-homogeneous displacement and vibration modes.

The full-field measurement of the vision method allows us to analyze the vibration modes of the membrane and rotations of rocking modes. Although a 3D method based on stereo vision for the whole video sequence is required to get accurate data on the entire surface of the membrane, the single-axis technique give us a relevant overview on the local properties of the vibrations at these particular frequencies. Using the same frequency sweep sequence from the previous analysis, it is possible to obtain a plot of an indicator of spatial differences in the movement of the membrane. A variance normalized by the mean displacement is used in Fig. 4 to detect the frequencies at which rocking (33.2 and 123.4 Hz) or vibration modes (339.8 Hz) manifest themselves. Note that the non-symmetric shape of the distribution of amplitude of displacements for the vibration mode at 339.8 Hz is due to the inhomogeneous sensitivity of the single-axis setup [11] being this, the cost of reducing the complexity and price of the setup.

The nonlinear force factor $Bl(x)$ estimation requires the measurement of voltage at the speaker at different displacements and velocities of the membrane. This is measured by inserting the speaker into the front opening of a wooden box (pointing outwards) which has an excitation speaker inserted at the back opening, membrane inwards. Thus, the excitation of the back speaker produces pressure variations inside the box that move the measured woofer without using an electrical excitation on it. This setup avoids imprecise manual movements of the loudspeaker as done in Ref. [11] and allows measuring velocity, and therefore displacement, using the laser vibrometer. A sinusoidal excitation with frequency 18.5 Hz (half of the resonance frequency) is used so that the amplitude of displacement is high enough to present non-linear effects. The displacement and velocity are measured by using the single-axis vision method, performing the calibration procedure before the measurement. A frame rate of 250 fps, 0.5 ms exposure time, and 2.2 s duration sequence is acquired comprising 550 frames. An initial image is taken before the sequence with the speaker at rest to set the ground level of the signal.

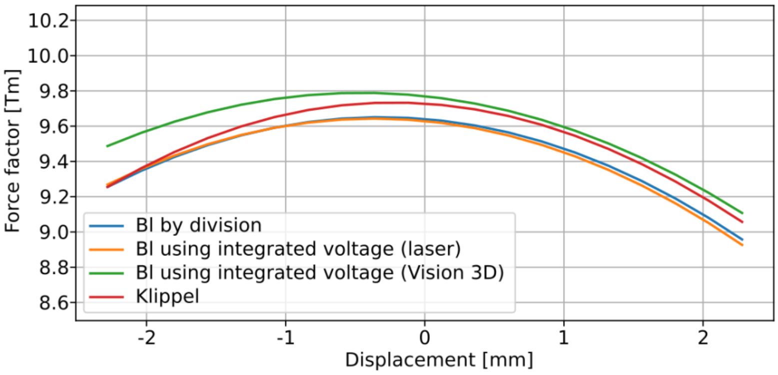

Figure 5: Obtained Bl curves using different estimation methods and measurement techniques.

Using the expression $U(t) = Blv(t)$, being $v(t)$ the velocity at a point, is simple to obtain Bl by plotting the points $(x(\mathrm{t}), U(\mathrm{t})/v(\mathrm{t}))$ in a chart and fitting a polynomial function $Bl(x) = Bl_0 + Bl_1 x + Bl_2 x^2$ at points where $v(\mathrm{t})$ is not close to zero. A different method using all measurements is based on the integrated voltage signal

$$\widetilde{U}(t) = \sum_{k=0}^{t} U(k)\Delta t = Bl_0\, x(t) + Bl_1 \frac{x^2(t)}{2} + Bl_2 \frac{x^3(t)}{3}, \tag{2}$$

for which a polynomial fit will obtain coefficients that can be simply turn into the polynomial expansion of $Bl(x)$ Fig. 5 shows the obtained curves of $Bl(x)$ using the direct division and integrated voltage methods for the laser measurements and the integrated voltage for the vision method at the center of the membrane. Also, the Bl measurement using a Klippel Distortion Analyzer 2 are shown as reference.

During the same measurement, a pressure-field microphone B&K 4938-A-011 is used to obtain the pressure inside the box. The pressure signal $p(t)$ is used to obtain the force over the membrane $F(t) = S_d p(t)$, which effective surface S_d is known. A linear regression method is then used to retrieve the stiffness parameter $K_{ms}(x)$ using the nonlinear model

$$F(t) = M_{ms}a(t) + R_{ms}v(t) + K_{ms}(x)x(t), \tag{3}$$

where $K_{ms}(x) = K_{ms0} + K_{ms1}x + K_{ms2}x^2$, with $a(t)$ the acceleration. Note that $v(\mathrm{t})$ and $a(t)$ are obtained from $x(t)$. The obtained resulting curves for K_{ms} are shown in Fig. 6. It is important to note that K_{ms} is frequency and amplitude dependent, so the differences between the Klippel curve and the other two may be due to the usage of different ranges of frequencies and amplitude levels during the measurements [16].

At last, a similar measurement setup is employed for the measurement of displacement, voltage, and pressure over a speaker PHL E172-16 SP1590 without drawings. A picture of the setup is shown in Fig. 7. The excitation was a 10 Hz tone burst with 40 cycles. The 1024 x 1024 pixels video sequence was acquired at 250 fps, with 1 ms exposure time. The displacement obtained by the single-axis vision method is presented in Fig. 8 along with the signal obtained by the laser vibrometer. It is possible to notice a slight difference of amplitude and some distortion effects, especially for the positive half cycles. A minimum calibration error may be responsible for this type of distortion but the overall aspect of the recovered signal is similar to the laser measurement, having low noise and a continuous behavior.

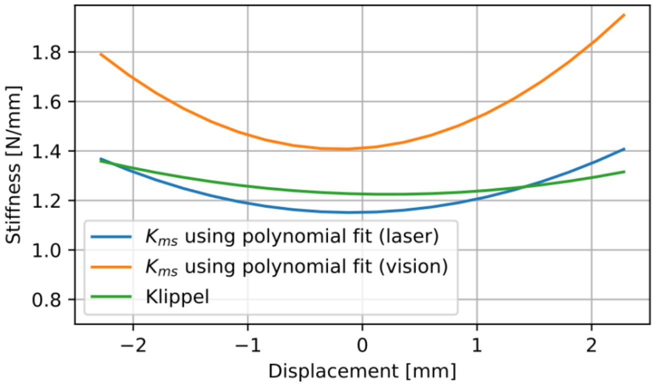

Figure 6: Measurements of stiffness K_{ms} using the Klippel system, the laser vibrometer, and the vision method.

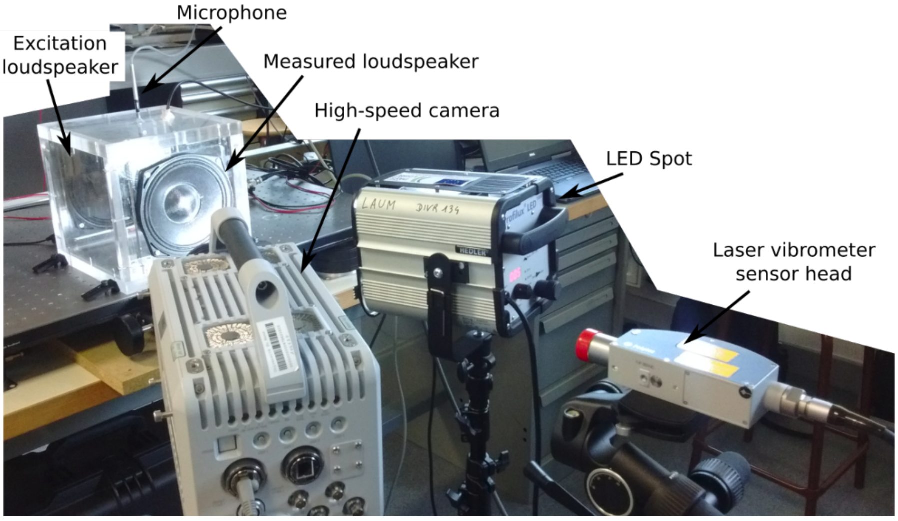

Figure 7: Single-axis vision method setup with box for acoustic excitation of loudspeaker.

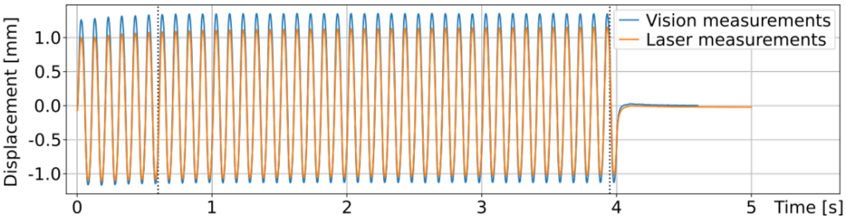

Figure 8: Displacement measurements in black loudspeaker without drawings.

3 CONCLUSIONS

The single-axis vision method was used for the measurement of displacement over the entire surface of one loudspeaker with inserted drawings. A fast characterization of spatial and linear properties of the loudspeaker was performed by analyzing a single video sequence when testing with a logarithmic chirp signal. The CWT ridge of the vibration signal at each measurement point was used to extract the instantaneous frequency, phase, and amplitude for a quick overview of vibration modes. Slower frequency sweeps or multitone signals should be considered for a more thorough analysis. An acoustic excitation box was employed for the measurement of nonlinear parameters, such as the force factor and stiffness of suspension, providing a controlled mechanical movement of the membrane with known applied force. The force factor coefficients were found by two different polynomial fitting approaches using the instantaneous measurements of displacement and: (a) force factor, and (b) integrated voltage. The resulting values were similar despite the second approach uses the entire set of data. The stiffness was obtained by a linear regression over a polynomial approximation of nonlinear parameters in the model describing the piston mode vibration. A good agreement was found by comparing the measured parameters against the results from a dedicated distortion analyzer. Finally, some promising results were shown about using the single-axis vision method in a loudspeaker without introducing any particular pattern on it. The normal direction on which the measurement takes place was extracted from the a priori information about the shape of the loudspeaker. Thus, a displacement measurement for the characterization of a loudspeaker was made available even without forcing a pattern in the membrane to perform the correlation tracking procedure which is a major drawback of this vision method.

ACKNOWLEDGEMENTS

The work presented here is supported by the institute ‘‘Le Mans Acoustique” and funded by the ‘‘Pays de la Loire” region and the ‘‘European Regional Development Fund”.

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