

# Localizing Acoustic Touch Impacts using Zip-stuffing in Complex $k$ -space Domain

R. Bremananth, Andy W. H. Khong, and A. Chitra

**Abstract**—Visualizing sound and noise often help us to determine an appropriate control over the source localization. Near-field acoustic holography (NAH) is a powerful tool for the ill-posed problem. However, in practice, due to the small finite aperture size, the discrete Fourier transform, FFT based NAH couldn't predict the active-region-of-interest (AROI) over the edges of the plane. Theoretically few approaches were proposed for solving finite aperture problem. However most of these methods are not quite compatible for the practical implementation, especially near the edge of the source. In this paper, a zip-stuffing extrapolation approach has suggested with 2D Kaiser window. It is operated on wavenumber complex space to localize the predicted sources. We numerically form a practice environment with touch impact databases to test the localization of sound source. It is observed that zip-stuffing aperture extrapolation and 2D window with evanescent components provide more accuracy especially in the small aperture and its derivatives.

**Keywords**—Acoustic source localization, Near-field acoustic holography (NAH), FFT, Extrapolation,  $k$ -space wavenumber errors.

## I. INTRODUCTION

**N**EAR-FILED acoustic holography (NAH) can classify into three types. In the first type, wavenumber decaying with the discrete Fourier transform is carried out. It has certain limitations due to finite aperture and divisibility of wavenumbers [1]. Another one is for composite geometries which utilized singular value decomposition in conjunction with inverse boundary elements [2]. However this method requires a minimum number of nodes per wavelength in order to achieve inverse prediction as a result large amount of measurements are required as compare to the former and it takes more time consumption in reconstruction. Helmholtz least squares is a third approach which is also employed for different kind of composite shapes. It uses spherical wave expansions and produces a destitute reconstruction as a result the accuracy decreases the source diverges from a spherical shapes. Thus, this paper belongs first category which is more suitable approach with planar geometry, in that, 2D Fast Fourier transform (FFT) allows to do multiplication with an inverse propagator and wavenumbers, which results in an extremely fast localization of the source distribution on active-region-of-interest (AROI). However, large aperture sizes with many measurement points, planar NAH is more

suitable. Whereas, in the case of less number of sensors with small aperture, it causes gradually more errors with respect to wavenumber outflow and localization deformations, especially neighborhood of the aperture edges. So that, this work suggests a solution to minimize the above said finite aperture problem.

In the literature many works have been done towards sound source visualization and localization, most of the schemes mainly focused on estimating acoustic pressure [3][4], but a few works documented towards vibrating sources [5]. The erroneous caused due to truncation effect on the pressure field was avoided using wavelet based multiresolution analysis by Thomas et al [6]. Patch NAH based decomposition of the transfer function using singular value decomposition and FFT was proposed in [7]. In that, an inverse transfer function was employed using Tikhonov regularization and the Morozov discrepancy principle. A wavenumber space extrapolation method was suggested to reduce the error in the reconstruction using boundary element NAH in [8]. Regularization based radiation field approximation was suggested in [9] and the so-called ill-posed problem had been resolved by truncated singular value decomposition and the system was also tested with vibrating plates using the boundary element method. A method proposed in [10] utilized a transfer matrix to define the of acoustic quantities on a mapping surface close to the measurement surface. In such way that propagating and evanescent waves were projected with optimal accuracy and an overview of the basic theory on statically optimized near-field acoustic holography (SONAH) was also dealt with. It removes spatial frequency domain completely, operates on plane-to-plane spatial domain and computes the inverse propagation using spatial convolution. However, this method employed with long computation due to the spatial convolution required to resolve the inverse solution.

In this paper, we focus on enhancing the localization touch impact source positions, especially near to the edges over the hologram plane. A finite aperture problem has been resolved by extending the aperture size virtually before computing on spatial frequency domain. It further ensures the minimum distortions close to edges of the measurement plane and accounts acceptable wavenumber leakage. This is accomplished by extrapolating the fixed size of the hologram by a zip-stuffing method. It stuffs the predicted impulses from the previous edges of the hologram to the extrapolated regions of the synthesized plane. In order to avoid the spatial window leakage, 2D Kaiser window has also incorporated to ensure the smooth data transitions. The rest of this paper is organized as follows. Section II deals the finite aperture and localization

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problems in the hologram edges. A suggested method is described in Section III. Section IV illustrates the experiments on numerical results on touch impact sources. Concluding remarks and further directions of research are discussed in Section V.

## II. FINITE APERTURE AND LOCALIZATION PROBLEMS

Finite aperture causes deformation in source localization near the AROI. It is mainly due to the quality of hologram, that is related with the quantity of microphones which we are utilizing for the measurement. The quality of the hologram data provides more information in the prediction process and it is directly related with the accuracy of the measurements. Furthermore, a spatial preprocessing method is required for improving the quality hologram data with the minimum number of measurement points. We must also note that the finite aperture and truncation influence the resolution of the predication. This is primarily due to the factor of using spatial FFT in NAH without using spatial preprocessing on the hologram plane.

In NAH, hologram plane is utilized to predict all acoustic measures from an infinite source of sound. However, in practice, this plane receives the sound pressure from the source plane as a form of discrete with a finite number of measurement points. Due to the discrete Fourier conversion over the finite measurement points on the hologram plane and its inverse transformation, the prediction of sources have the wraparound errors. A finite measurement can represent either by a rectangular or window function. They are mainly employing to determine the quality of data acquisition during the measurement. We can define a spatial rectangular function in  $x$  and  $y$  directions. In addition to the time discretization sampling, an acoustic imaging of the discrete system requires spatial sampling to the finite number of sensor positions with the finite spatial intervals. The impulse train function is used to represent spatial sampling in the acoustic imaging as

$$\begin{aligned} I(x) &= \sum_{n=-\infty}^{\infty} \delta(x - x_n), \\ I(y) &= \sum_{m=-\infty}^{\infty} \delta(y - y_m), \end{aligned} \quad (1)$$

where  $\delta()$ ,  $I(x)$ ,  $I(y)$ ,  $x_n$  and  $y_m$  represent respectively, Dirac delta function, impulse train functions, spatial discrete coordinates in  $x$  and  $y$  directions. We can describe the pressure as

$$p(x_n, y_m) = p(x, y) R_{sx}(x) R_{sy}(y) I(x) I(y), \quad (2)$$

where  $R_{sx}$  and  $R_{sy}$  denote respectively, spatial rectangular function in  $x$  and  $y$  directions. Finite boundary of the hologram plane in  $k$ -space can be computed based on the angular spectrum and a wavenumber vector  $|\mathbf{k}| \equiv (k_x, k_y)$  as

$$p(|\mathbf{k}|, z_h) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} p(x_n, y_m) e^{-j2\pi(k_x n/N + k_y m/M)}. \quad (3)$$

Discrete solution to the wave equation in  $k$ -space can be written as

$$p(|\mathbf{k}|_{n,m}, z) = p(|\mathbf{k}|_{n,m}, z_h) e^{jk_z(z-z_h)}. \quad (4)$$

In  $k$ -space,  $k_z$  is determined as

$$k_z = \pm \sqrt{k^2 - |\mathbf{k}|^2}. \quad (5)$$

It can provide a solution for propagating waves,  $|\mathbf{k}|^2 = 0$  and  $|\mathbf{k}|^2 \leq k^2$  denote respectively, plane waves in  $z$ -direction and  $k_z$  is real. Evanescent wave components are represented by  $|\mathbf{k}|^2 > k^2$  and  $k_z$  is complex. We can also define that wave equation lies exactly at  $k^2 = |\mathbf{k}|^2$ , inside the radiation circle implies the propagating waves and outside the radiation circle signifies the evanescent waves. If propagation constraint apply to the discrete wave equation (4) then it reveals the phase shift as a result whereas, in  $k$ -space, evanescent waves are increasingly multiplied by exponentially power of  $k_z$ . For this reason, before performing FFT and wavenumber operations over the measured hologram data, we possibly do the spatial preprocessing. In order to reduce the leakages, due to the higher evanescent wavenumber and signal distortions, we can do the process of anti-leakage window. A finite aperture is a collection of sensor array which is used for measurements. It is spatially experimented by a truncation window. There is no direct sampled acquaintance of the sound field in the outside the measured aperture. Consequently, the  $k$ -space is also resolved from the ill-mannered, spatially sampled and finite aperture. The choice of a windowing function is scrutinized as a procedure to diminish the order of the discontinuity at the edge of the intermittent extension of the aperture. The edges over the hologram plane can be predicted either by smoothly attenuating the data near the edges to zero or extrapolating / interpolating sampled data on the partially sampled regions.

Since unknown pressure outside of the hologram aperture is predicted, we have to consider the wavenumber, if a basis set of  $N$  intervals is defined, then certain existing signals in the defined set with a wavenumber not exactly fitting on one of the basis. The windowing function transforms this signal to the basis wavenumber closest to the original wavenumber of the signal leakage, therefore,  $k$ -space spectrum resolution is low. The aperture discontinuous edge indicates the presence of non-appropriate intermittent signals. It causes leakage to a large number of wavenumbers. This means that only ill-mannered aperture data are available and involves an important process to determine the suitable  $k$ -space with as much conserved spatial data as possible. In addition to that, it implies a relationship between the amount of  $k$ -space leakage and loss of acoustic pressures, principally in close proximity to the edges. A method is required to stuff the acoustic data in the edges of the hologram plane outward, while the true pressure data within the predetermined aperture is unaffected. It tends to localize entire source of the surface with minimum number of leakage at the  $k$ -space domain.

In  $k$ -space,  $k_z$  is determined, a solution for propagating waves,  $k_x^2 + k_y^2 = 0$  and  $k_x^2 + k_y^2 \leq k^2$  denote respectively, plane waves in  $z$ -direction and  $k_z$  is real. Evanescent waves components are represented by  $k_x^2 + k_y^2 > k^2$  and  $k_z$  is imaginary.

If propagation constraints apply to the discrete wave equation then it reveals the phase shift as a result whereas in  $k$ -space, evanescent waves are amplified through multiplication with an exponentially increasing power of  $k_z$ . For this reason, before performing DFT and wavenumber operations over the measured hologram data, we possibly do the spatial preprocessing. In order to reduce the leakages on the hologram plane due to the higher evanescent wavenumber and signal distortions, we can do the process with an anti-leakage window. The finite aperture is a collection of sensor array which is used for measurement at hologram plane. It is referred as a spatially truncation window. There is no direct sampled data of the sound field outside the measured aperture. This is illustrated in Fig. 1. Consequently, the  $k$ -space is also resolved from the ill-mannered, spatially sampled and finite aperture. The choice of a windowing function is scrutinized as a procedure to diminish the order of the discontinuity at the edge of the intermittent extension of the aperture. Fig. 1 also shows the problem of the finite aperture, in that, the edges over the hologram plane can be predicted using DFT with wavenumber either by smoothly attenuating the data near the edges to zero or extrapolating sampled data on the partially sampled regions. It may cause the problem of computational complexity to localize the source especially over the edges on the hologram plane.

Furthermore, we have to predict the unknown pressure outside of the hologram aperture. If the wavenumber of  $N$  basis set of intervals is defined then there exists a signal in the defined set with a wavenumber not exactly fitting on one of the basis. The windowing function transforms this signal to the basis wavenumber closest to the original wavenumber of the signal, therefore,  $k$ -space spectrum resolution is low. The discontinuous edge between aperture and measured area indicates the presence of non-appropriate intermittent signals. It causes leakage of wavenumber spectrum. This means that only ill-mannered aperture data are available and an important process should be involved to determine the suitable  $k$ -space with as much conserved spatial data as possible. In addition to that, it implies a relationship between the amount of  $k$ -space leakage and loss of acoustic pressures, principally in close proximity to the edges.

In order to make an interpolation among the basis of wavenumbers, we can possibly utilize zero samples on the edges. So that, we can possibly apply FFT on the zero-padded spatially sampled data and  $k$ -space spectrum. The discrete  $k$ -space is a conspiring of the continuous spectrum on the set of available basis of  $k$ -bins in the wavenumber domain. It has the remaining set of unknown spatial data in  $k$ -space to exactly match the discrete of the wavenumbers due to its periods. An imperfect resolution occur in  $k$ -space is mainly due to finite length of the spatial aperture. We extrapolate the new samples with zero value then it increases the spatial aperture and computing power of the FFT. For example, if every single portion increases higher than the actual aperture size then it reflects the numbers of bins  $b$  in  $k$ -space as  $k = 2\pi/(N + b)$ . A greater number of wavenumbers are distinguished from the spectrum. A practical problem encountered for extrapolating zero-padding is the calculation of FFT. By expanding the  $N$  samples by  $n$  samples, it demands

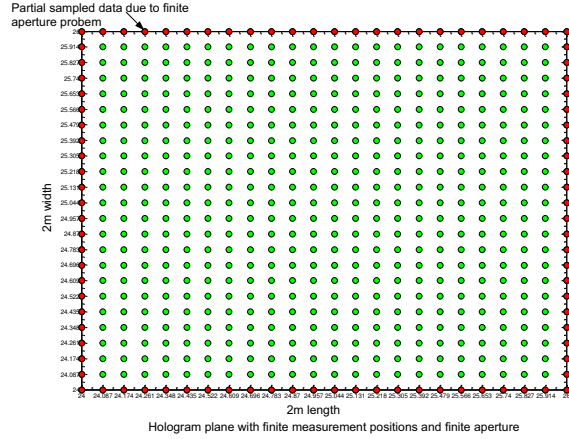


Fig. 1. Finite aperture problem and partially measured data at hologram plane. Size of the aperture is  $2 \text{ m}^2$ .

$O(N + n \log N + n)$  computational complexity then it causes more computation over the source localizations. In order to avoid the computational complexity and enhance the spectral resolution over the wavenumbers. We suggest a method to stuff the predicted samples over non-measured regions. It intends to improve the resolution of the localization in full area of the prediction plane.

### III. EXTRAPOLATING THE APERTURE USING ZIP-STUFFING

The idea behind in the zip-stuffing is to enlarge the hologram aperture without affecting the true measured pressure from the touch source. Samples are predicted based on the impulses of the edges and stuffed with the predicted samples. After extrapolating with predicted samples, a 2D Kaiser spatial window is applied on the entire data sets including the zip-stuffed portion. Since Tukey window causes more leakage factor Kaiser window has been unutilized. This synthesized plane is transformed into Fourier based complex  $k$ -space for back propagation. Dimension of the hologram plane is  $h_m, h_n$  partially sampled signals are synthesized by the predicted samples in close to the edge positions by enlarging the hologram data. Sampled data of the measurement plane is synthesized as (6), (7), (8) and (9) represent  $z_1, z_2, z_3$  and  $z_4$  regions of zip-stuffing in the counterclockwise direction, respectively,

$$z(z_m, z_n) = \begin{cases} p(h_m, h_n), & h_m > (h_m/2) \text{ \& } h_n > (h_n/2), \\ z_l(\hat{m}, n), & z_m \geq h_m \text{ \& } z_n \geq h_n, \end{cases} \quad (6)$$

$$z(z_m, z_n) = \begin{cases} p(h_m, h_n), & (h_m/2) > 1 \text{ \& } h_n > (h_n/2), \\ z_l(\hat{m}, n), & z_m \geq (h_m/2) \text{ \& } z_n \geq h_n, \end{cases} \quad (7)$$

$$z(z_m, z_n) = \begin{cases} p(h_m, h_n), & (h_m/2) > 1 \text{ \& } (h_n/2) > 1, \\ z_l(\hat{m}, n), & z_m \geq (h_m/2) \text{ \& } z_n \geq (h_n/2), \end{cases} \quad (8)$$

$$z(z_m, z_n) = \begin{cases} p(h_m, h_n), & h_m > (h_m/2) \ \& \ (h_n/2) > 1, \\ z_l(\hat{m}, n), & z_m \geq (h_m) \ \& \ z_n \geq (h_n/2), \end{cases} \quad (9)$$

where  $z(z_m, z_n)$ ,  $p(h_m, h_n)$  and  $z_l(m, n)$  denote respectively, synthesized planar, measurement planar and predicted impulse responses using predictive filter. In practice, while localizing AROI at the edges, it is an essential to expand the measured aperture and ensure that AROI is not positioned in close proximity to the perimeter of the edges. However, our approach ensures to localize sources near to the perimeter of the measurement plane and makes the smooth transitions without misplacing the original measured signals.

In order to determine impulses outside the hologram aperture, the first order derivative of edges are used to predict the samples. Least-square predictive coding (LSPC) is a concept to predict filter coefficients either by forward or backward. It minimizes the prediction errors in least squared manner. This technique is commonly used for speech synthesis and recognition. In that, it estimates the dominant frequencies of the received signals by analyzing a sound signal spectral peaks of the spectrum. Here, we employ LSPC for determining edge samples of a hologram from its adjacent samples as

$$z_l(\hat{m}, n) = - \sum_{i=1}^q \sum_{j=1}^r a_f(i, j) p(h_m - i, h_n - j), \quad (10)$$

where  $z_l(\hat{m}, n)$  and  $a_f(i, j)$  represent respectively, the predicted signal of  $p(h_m, h_n)$  and the prediction coefficients. The order of the filter coefficients is determined by  $q \times r$  and  $(m, n)$  characterizes the boundary-of-support (BOS) of the predictor. Besides the coefficients of  $q \times r$  order FIR filter is used to predict the outward samples based on prior region of samples in the hologram.

Normally, autoregressive model estimation is a main concerned, if the autocovariance matrix is inadequately insured then the relatively large deviation in the parameters estimations due to small covariance estimate bias. It results an invalid estimation model. So that, autoregressive model fits all estimated poles exactly on unit circle. This is a case we consider in our estimation with LSPC.

#### A. Least-squares aptitude

A discrete set of hologram data  $p(h_m - 1, h_n - 1)_{m,n \in [0, M-1, 0, N-1]}$  is used to predict unknown samples  $z_l(\hat{m}, n)_{m,n \in \mathbb{Z}}$ . A common way of minimizing the prediction error in choosing the filter coefficients is based on the least-squares aptitude. Possibly, we want to predict the best  $q \times r$  coefficients  $a_f(m, n)_{m \in [1, q], n \in [1, r]}$ , with the intension that to minimize the sum of the squares of the error between the true neighborhood and anticipated impulses. The prediction and mean-squared errors are described such as  $e(m, n)$  (11) and  $\varepsilon^2$  (12), respectively, where  $E[\bullet]$  is probability of error's expectation operator. In practice, the prediction error pressures must have a smaller dynamic range and a more non-uniform distribution than the true pressure. A set of optimal predication coefficients is used to minimize the mean-squared error. 2D covariance matrix  $\Sigma$  has been determined by solving a

diagonal-constant matrix  $D$ , i.e.,  $\Sigma = DD^H$ . The total squared error of the regions  $z_1, z_2, z_3$  and  $z_4$  are obtained as

$$E^i = \sum_m^{BOS_m} \sum_n^{BOS_n} e^i(m, n)^2 = a^i \Sigma a^{iH}, \quad (13)$$

$$DD^H = \sum_m^{BOS_m} \sum_n^{BOS_n} p(h_m, h_n) p(h_m, h_n)^H. \quad (14)$$

In order to minimize the total squared error 2D autoregressive parameters  $E^{1 \dots 4}$  are computed.

#### B. Wavenumber transforming in Complex space

Complex wavenumber is utilized for locating AROIs. The synthesized plane is used for transforming measured pressure into Fourier coefficients. The size of the wavenumber is determined based on the synthesized plane as,  $k_n, k_m$  and generate linearly spaced vectors for structural wavenumbers viz  $\Delta k_x = \frac{\pi}{z_m \Delta}$  and  $k_x = (-\frac{z_m}{2}, -\frac{z_m}{2} + 1, \dots, \frac{z_m}{2} - 1) \times \Delta k_x$ , and  $\Delta k_y$ . The wavenumber  $k_y$  is determined the same. Perform FFT over synthesized zero-padded data and compute  $\Delta_{dx}$  and  $\Delta_{dy}$  for wavenumber spacing between  $x$  and  $y$  directions respectively as

$$\Delta_{dx} = (2\pi/\Delta_x)/z_m, \quad (15)$$

$$\Delta_{dy} = (2\pi/\Delta_y)/z_n. \quad (16)$$

where,  $\Delta_x$  and  $\Delta_y$  represent sensor spacing in  $x$  and  $y$  directions of the synthesized plane respectively. In order to do the wavenumber transforming and inverse propagation, the following operations are performed as follows

$$k_{pro} = k^2, \quad (17)$$

$$k_x = \Delta_{dx}(k_{xi} - 1), \quad (18)$$

$$k_y = \Delta_{dy}(k_{yi} - 1), \quad (19)$$

$$k_{xy} = k_x^2 + k_y^2, \quad (20)$$

$$(21)$$

$$p(k_x, k_y) = \begin{cases} k_z = \sqrt{k_{pro} - k_{xy}}, \\ z(z_n, z_m) e^{(ik_z z_d)}, & \text{if } (k_{pro} > k_{xy}), \\ k_z = \sqrt{k_{xy} - k_{pro}}, \\ z(z_n, z_m) e^{(-k_z z_d)}, & \text{otherwise} \end{cases} \quad (22)$$

where  $p(k_x, k_y)$  and  $z_d = z_h - z_s$  denote wavenumber coefficients, the distance between hologram and source, respectively. After wave transforming, backward prediction and inverse FFT are carried out to localize the AROIs. Naturally, a kind of jagged truncation is produced by the finite aperture. It causes impractical wavenumber artifacts. For getting smooth data transition between source and measurement planes, we can use a windowing. The high wavenumber artifacts have minimized by applying 2D Kaiser windowing with zip-stuffing. Un-fitting periodic signals and high wavenumber artifacts are occurred during the measurement that can be minimized by employing 2D Kaiser window. This is illustrated in Fig. 2.

In order to reduce the wavenumber leakage after transforming spatial data by Fourier to the wavenumbers a spatial

$$e(m, n) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \left( p(h_m, h_n) - \left( -\sum_{i=1}^q \sum_{j=1}^r a_f(i, j) p(h_m - i, h_n - j) \right) \right)^2,$$

$$e(m, n) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \left( p(h_m, h_n) + \sum_{i=1}^q \sum_{j=1}^r a_f(i, j) p(h_m - i, h_n - j) \right)^2, \quad (11)$$

$$\varepsilon^2 = E[e(m, n)^2]. \quad (12)$$

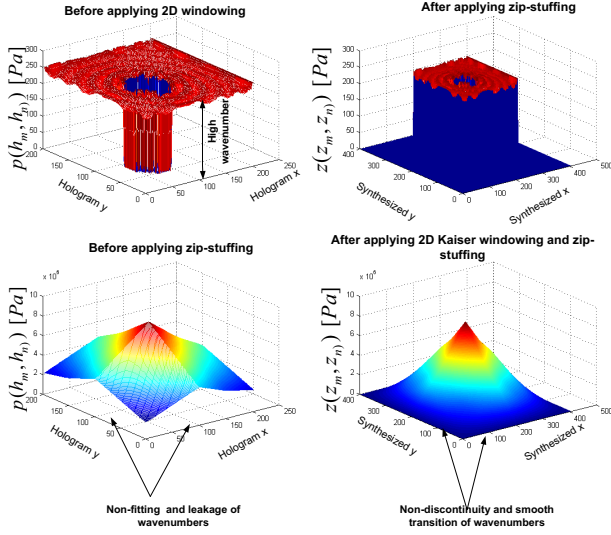


Fig. 2. The effect of minimizing artifacts by applying windowing and zero-padding on the measurement and synthesized planes.

window is required. As compare with Tukey window, 2D Kaiser accounts small spectral leakage and increases amplitude accuracy. Since the Bessel based 2D Kaiser window has been employed in the spatial source processing. Especially, it ensures leakage outside the circle to wavenumbers and the smooth transition of data between source and hologram planes. In view of the fact that increasing evanescent components outside the circle are computed by an exponential power, the back propagated spectrum contain leakage of data that can impinge on the spatial data of the prediction. Furthermore, we have to do the inverse process to avoid the magnification of errors present in the evanescent components due to exponentially decaying in the localization. Because of spatial preprocessing, the resolution of source localization will be improved and predicted source can exactly localize in near the edge of source as well. Here, the wavenumber complex-space is incorporated with real-space for localizing impact point source. The spatial FFT is used for the prediction process, in that, transformed pressure coefficients are computed by exponential of  $k_z$  and  $z_d$ . This has been carried out, if  $k$ -space points are within or on the radiation circle. If  $k$ -space points are outside the radiation points then pressures coefficients are calculated by exponential of inverse complex-space,  $k_z$  and  $z_d$ . The wavenumber response of the pressure coefficients

are computed and their absolute deviations are studied. It shows that transforming coefficients in complex space domains (evanescent) is essentially involved in predicting the sources of the entire surfaces regions.

#### IV. RESULT ANALYSIS

The implementation and result analysis have been done in MatLab 7.10. The source points over the edges in the  $k$ -space cause more error in the NAH. In order to evaluate the performance of our extrapolation method, we conducted experiments on the edges of the hologram plane with diverse point sources. We evaluate the point sources reconstruction based on the qualitative and quantitative analysis. Quantitative analysis provides the primary connection between ground truth of the observation and reconstruction in the NAH. Two types of evaluation have been carried out, one is a statistical reconstruction error (SRCE) and the another is a root mean square reconstruction error (RMSRCE). The SRCE evaluates the hypotheses which is based on the standard deviation of residuals error between ground truth pressure,  $P$  and reconstruction or estimated pressure,  $\hat{P}$  dividing by maximum absolute deviation of ground truth  $P_m$ . This is described as

$$R = P - \hat{P}, \quad (23)$$

$$P_m = \max(|P|), \quad (24)$$

$$R_c = 100 * \frac{\sqrt{E[(R - \bar{R})^2]}}{P_m}, \quad (25)$$

$$(26)$$

where  $R_c$ ,  $R$ ,  $\bar{R}$  and  $P_m$  denote, respectively, statistical reconstruction error, residuals, mean of the residuals and maximum absolute deviation of ground truth. Another method RMSRCE is also an quantitative analysis. It resolves the hypotheses between ground truth and estimated pressures, denotes square root of absolute deviation mean difference between  $P$  and  $\hat{P}$  by dividing mean of the absolute deviation of  $P$ . This is represented as

$$R_m = \sqrt{\frac{E[P - \hat{P}]^2}{E[P]}}. \quad (27)$$

Besides quantitative analysis, we have performed the process of qualitative analysis to evaluate the reconstructed pressure source. The main objective of this analysis is to determine the dominance of subjective of hologram interpretation. Whereas quantitative methods can be used to verify the dominance of statistical information to which of hypotheses

are true. Based on qualitative measures, we conducted two phases of measures such as modal assurance criterion (MAC) and peak-signal-to-noise ratio (PSNR). MAC is an attribute to evaluate the consistency or degree-of-linearity between reconstruct and ground truth reference sources. It provides an additional confidence factor in the evaluation of a modal vector from different excitation locations or different modal parameter reconstructions. The MAC takes on values from 0 to 1, representing an inconsistent and a perfect consistent of the reconstruction pressure, respectively as

$$MAC = \frac{\sqrt{E[P\hat{P}^*]E[P^*\hat{P}]}}{\sqrt{E[P^*P]E[\hat{P}^*\hat{P}]}} \quad (28)$$

where  $P^*$  and  $\hat{P}^*$  denote conjugate transpose of reference and estimate sources, respectively. If the MAC has a value near zero, this is an indication that the estimated pressures are inconsistent. This is due to non-stationary of signals, noise on the sources, error in parameters, and others. If the system is nonlinear and two data sets are acquired at diverse timings or excitation levels then non-stationary of signals are present. Furthermore, nonlinearities may appear in a different way of frequency response functions generated from different electrifier positions or excitation signals. For these reasons, estimation algorithms may not handle the different nonlinear characteristics in a reliable manner. Next, the MAC has a value near unity, this is an indication that the source and estimated pressures are reliable.

The third qualitative judging measure is PSNR. It is usually utilized by the image processing communities as a measure to evaluate the quality decomposition or restoration of reconstruction images. PSNR has a higher value is an indication of better reconstruction of ground truth signals. This is computed based on the ratio between the maximum possible of a pressure signal and the root-mean-square error (RMSE). Residuals between the ground truth and estimated pressures are computed then its conjugate root-mean-square has been taken for the RMSE computation as

$$RMSE = \sqrt{E[R^{*2}]},$$

$$PSNR = 20 \log_{10} \left( \frac{\max |P|}{RMSE} \right). \quad (29)$$

Fig. 3 shows the results of applying zero-padding with respect to various above said evaluation metrics. After applying 2D kaiser windowing and zip-stuffing the performance of the evaluation metrics are improved significantly as shown in Fig. 4. This reveals that the propose method contribute significant improvement on the real-life extrapolation in the localization of acoustic impacts. In addition to these four measures we analysis the practicability of the suggested algorithms with different parameters such as standoff distance, frequency variations, sampling frequency, diverse off-sets in sensor grids, sensor spacings and assorted ratio of measurement aperture to the source plane.

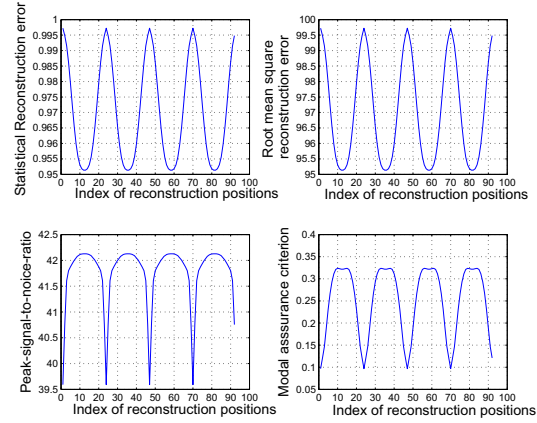


Fig. 3. Result of windowing and zero-padding in increasing statistical reconstruction and RMSE errors. Lower PSNR and MAC.

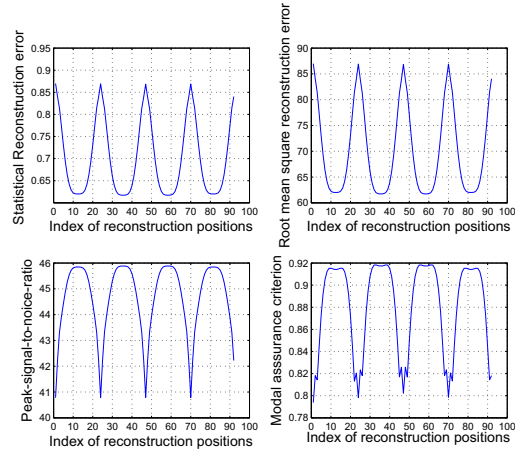


Fig. 4. Result of windowing and zip-stuffing in minimizing statistical reconstruction and RMSE errors. Improved PSNR and MAC in the synthesizing.

## V. CONCLUSION

In this paper, a method of source localization based on zip-stuffing extrapolation with 2D Kaiser window was proposed. Our main contribution was a 2D based linear extrapolation approach in the NAH. In order to localize the source in the small aperture of hologram, we proposed zip-stuffing extrapolation. The reconstruction of prediction plane was also done to retrieve an enhanced version of the measured pressure. It assisted us to reinstate sufficient magnitude of unmeasured data from the ill-posed data set. This work opens a new era of research to localize the source in the NAH with small size aperture hologram. In near future, an efficient non-linear extrapolation will yet to be suggested to enhance the hologram further and remove the truncation effects transpire on the finite



aperture to minimize the large measurements positions.

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