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VisualizationofRotatingMachineryNoiseBasedonNear FieldAcousticHolography

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Abstract

In order to study the problem of rotating mechanical noise source identification, a time-space complex envelope model of monopole sound source is proposed, and the modulation method of complex envelope is given. According to the characteristics of the acoustic field radiation of the rotating mechanical noise source, different measurement distances, reconstruction distances and measurement points are selected to reconstruct the sound field. The simulation analysis results show that the near-field acoustic holography technology still obtains high acoustic field reconstruction accuracy under the condition of large reconstruction distance and requires few sampling points. Even with less measurement points, this method can obtain a better accuracy of acoustic field reconstruction. Using the envelope modulation technique to extract the envelope information and reconstruct the acoustic field can accurately identify the number of sound sources and geometric position distribution, speed up the data processing speed and ensure the reconstruction accuracy of the acoustic field.

Keywords:*near field acoustic holography; rotating machinery; spatial envelope; envelope modulation*

1.Introduction

Near-fieldacousticholographyisaneffectiveacoustici magingtechniqueproposedbyJDMaynardandEGWilli amsetal.inthe1980s.Itobtainsthesoundfieldinformatio nofunknownnoisesourcesthroughhydrophonesfixedo nthemeasuringsurface.Theholographicalgorithmwas usedtoreversethesoundsourceinformationtorealizethe identificationandlocalizationofthenoisesource[1].With theeffortsofscholars,thenear-fieldacousticholography technologyhasdevelopedrapidly.In2001,HaldJproposedtheTimeDomainHolographymethod[2].Thebasicpri nciplewastointerceptthesignalofasmalltimeperiodinth elong-timesignalforanalysis,andthentheresultwasobta ined.Thismethodsuccessfullyrealizedthesoundfieldre constructionofmotorcyclebrakenoise.In2004,Ombeli neusedthenear-fieldtime-domainplanescanningmetho d[3]andproposedfourtime-domaincalculationmethodst opredictthetransientsoundpressurefield.Theparamete rsthataffectthetransientsoundfieldreconstructionaccur acywereanalysedinsimulation,andthesoundfieldrecon structionaccuracyofthefouralgorithmsunderdifferentc onditionswascalculated.In2009,ParkandKimusedthet ime-domainnear-fieldacousticholographytechnologyt ovisualizethespatialcomplexenvelope[4-5].Paillasseur psandThomasvalidatedthealgorithmbyusingregulariz ationmethodstoimprovethedeconvolutionprobleminr eversesoundfieldreconstructionandtheimprovedsoun dfieldreconstruction[6-9].In2016,Keferintroducedther oboticarmintothemeasurementofnear-fieldacousticho lography,whichreducedthenumberofmicrophonesand acceleratedthemeasurementspeed,andstudiedstatican ddynamicnear-fieldacousticholography[10].Haldprop osedthewidebandholography.Onlyasinglemeasureme

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ntwasrequiredoverarelativelyshortdistancetoobtainasingleresultcoveringtheentirefrequencyrange[11].In2018,Chaitanya,S.Ketal.usedcylindricalnear-fieldacoustiholography(NAH)tolocatethecylindricalsurfacesoundsource,andcomparedthedirectNAHwiththesoundfieldspatialtransformation(STSF).Bothmethodsgavethecorrectsoundsourcelocalization[12].In2019,JiangLaixuproposedtousetheimprovedTikhonovregularization(MTR)methodtosolvethewindingerrorscausedbythewindowfunctionandotherill-posedproblems,effectivelyimprovingthespatialresolutionofthereconstructedsoundfield[13].ShiDongyangcombinedthewidebandacoustiholographytechnologyandl(1)-normconvexoptimizationtosolvetheinverseproblemofsoundfieldreconstruction.Usingtheadvantagesofthetwomethods,ahybridmethodcombiningthebestfeaturesofthetwomethodswasproposedtoidentifythesoundsourcelocation[14].Antoni,Jusedaniterativemethodtoautomaticallyestimatetheaperturefunction,andsimultaneouslycompletedthecalculationoftheaperturefunctionandthesoundsourcedistribution[15].

Largestructuresoftencontainvariousoperatingmachines,equipment,power,andpropulsionsystems.Whenaworkingmachinemalfunctions,asoundspaceenvelopemayappear.Theenvelopeinformationcontainssoundfieldfeatureinformationandsourceinformation.Byextractingtheenvelopeinformationofthesignalandusingittoreconstructthesoundfield,thepositioninformationandgeometricinformationofthesoundsourcecanbeobtained.Inordertoanalysethesoundsourcecharacteristicsofsuchrotatingmachinery,itisproposedtousethespatialenvelopeofthesoundfieldtoidentifyandanalysethenoiseoftherotatingmachinery.

2.Near-fieldacoustiholography

Accordingtothewaveequationofsmallamplitudeacoustic waves in an ideal fluid medium, the steady-state sound field Helmholtz equation independent of time variables can be obtained:

$$\nabla^2 p(\vec{r},\omega) + k^2 p(\vec{r},\omega) = 0 \qquad (1)$$

Where: $p(\vec{r},\omega)$ is the complex sound pressure of the spatial point, $k = \omega/c = 2\pi/\lambda$ is the wave number in the fluid medium, ω is the angular frequency of the sound wave, and λ is the characteristic wavelength. First, define H as a holographic surface (measurement surface), S as a reconstruction surface (source surface), and source surface S may be any surface surrounding the sound source.

The Green's function satisfies the Dirichlet boundary condition on S, When the space of $z_H > z_S$ is a free field, the solution of any point of Eq(1) can be obtained by the Green's function formula:

$$p(x,y,z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x_S,y_S,z_S)\cdot g_D(x-x_S,y-y_S,z-z_S)dx_S dy_s \qquad (2)$$

If the sound pressure on the $z = z_S$ plane where the sound source is located is known, the sound pressure on any plane of the $z > z_S$ space can be found. Defining the relation between two-dimensional continuous Fourier transform and inverse transform in the x, y direction along the space.

$$P(k_x,k_y,z) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x,y,z)\, e^{-j(k_x x+k_y y)}dxdy \qquad (3)$$

$$p(x,y,z) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(k_x,k_y,z)\cdot e^{j(k_x x+k_y y)}dk_x dk_y \qquad (4)$$

Where $P(k_x,k_y,z)$ is the angular spectrum of $p(x,y,z)$, and k_x, k_y are the wavenumber components in the x, y direction, respectively.

After performing two-dimensional space Fourier transform on Eq(2), the convolution theorem is used to convolve the space into the product of the angular spectrum in the wavenumber domain.

$$P(k_x,k_y,z) = P(k_x,k_y,z_s)\cdot G_D(k_x,k_y,z-z_S) \qquad (5)$$

In the formula, $P(k_x,k_y,z_S)$ and $G_D(k_x,k_y,z-z_S)$ are two-dimensional Fourier transforms of $p(x,y,z_S)$ and $g_D(x,y,z-z_S)$, respectively.

The two-dimensional space Fourier transform expression of Green's function under Dirichlet boundary condition is

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$$G_D(k_x, k_y, z - z_S) = e^{j k_z (z - z_S)} \quad (6)$$

Where

$$k_z = \begin{cases} \sqrt{k^2 - k_x^2 - k_y^2} k \geq \sqrt{k_x^2 + k_y^2} \\ i\sqrt{k_x^2 + k_y^2 - k^2} k < \sqrt{k_x^2 + k_y^2} \end{cases} \quad (7)$$

TaketheinverseFouriertransformonbothsidesofEq(5)toobtaintheH-planesoundpressure

$$p(x, y, z_H) = F^{-1}\left(F(p(x, y, z_S)) e^{j k_z (z_H - z_S)}\right) (8)$$

Where F and F^{-1} representtheFouriertransformandtheinversetransformintwodimensions,respectively.

Thefarfieldpredictionofthesoundfieldcanbecompleteddaccordingto Eq(8),andthenearfieldreconstructionofthesoundfieldamountcanberealizedbyEq(10).

Whenthevalueofthesoundpressureon $z = z_S$ isknown,thesoundpressurevalueonanyplaneof $z > z_S$ canbepredicted.Conversely,theequation(5)byperformingyields:

$$P(k_x, k_y, z_S) = P(k_x, k_y, z_H) \cdot e^{-j k_z (z_H - z_S)} (9)$$

Usingtheaboveequationtoobtainthesoundpressurenearthesurface $z = z_S$ (reconstructionsurface).Thebasicformulaforplanar near-fieldacousticholographicreconstructioncanbeobtained:

$$p(x, y, z_S) = F^{-1}\left(F(p(x, y, z_H)) e^{j k_z (z_H - z_S)}\right) \quad (10)$$

Inthereversereconstructionofthesoundfield,theimprovedtwo-dimensionalHarrisfilterwindowfunctionisusedtofilterthenoisesignalinthewavenumberdomain:

$$W(k_x, k_y) = \begin{cases} (k_r/k_c - 1)\left(1 - 1/2 e^{(k_r/k_c - 1)/\alpha}\right), k_r \leq k_c \\ (k_r/k_c - 1)\left(1/2 e^{(1 - k_r/k_c)/\alpha}\right), k_r > k_c \end{cases} \quad (11)$$

Where $k_c = 0.6\pi / \Delta$ isthecut-offwavenumberofthefilter,Δisthemeasuringdistanceofthemeasuringsurface. $k_r = \sqrt{k_x^2 + k_y^2}$;αisthesteepnesscoefficientofthewindowfunction.Whenαissmaller,thefunctionvaluecutoffsteeperatk_c.Generallyαiswithin0.1~0.2.

3.Time-spacecomplexenvelopemodel

Inthepropagationofsound,theacousticwavecharacteristicsarerelatedtothewavelength($\lambda = c/f$)inbothtimeandspace,sothetimecomplexenvelopeofanarrowbandsignalcanalsocausethespacecomplexenvelopeassociatedwithit.Thespacecomplexenvelopebedefinedinthesamewayasthetimecomplexenvelopeisdefined.Takingthemonopolesoundsourceasanexample,therelationshipbetweenthespacecomplexenvelopeandthetimeenvelopeisderived

Supposeapointsoundsourcewithslowamplitudechangesradiatesoutwardatthecenterfrequency f_c ,anditssoundpressure$p(\vec{r}, t)$is

$$p(\vec{r}, t) = a(\vec{r}, t) \frac{e^{-j(2\pi f_c t - k_c R + \Phi_t + \Phi_s)}}{R} \quad (12)$$

Where Φ_t isthetimephaseand Φ_s isthespacephase, $k_c = 2\pi f_c / c$ isthewavenumber,Risthedistancebetweenthemeasurementpointandthesoundsource.

DividetheamplitudeinEq(12)intotwoparts:oneisrelatedtothecenterfrequencyf_c,andtheotherisrelatedtotheslowlychangingamplitude$a(r, t)$andphaseΦ_t, Φ_s:

$$p(\vec{r}, t) = \frac{a(\vec{r}, t) e^{-j(\Phi_t + \Phi_s)}}{R} e^{-j(2\pi f_c t - k_c R)} \quad (13)$$

Thetime-spacecomplexenvelopeisexpressibleas:

$$p_{CE}(\vec{r}, t) = \frac{a(\vec{r}, t) e^{-j(\Phi_t + \Phi_s)}}{R} \quad (14)$$

Intheaboveformula, $a(r, t)$ canbewrittenasthesumofafiniteenumberoffrequencycomponentsinanarrowband:

$$a(\vec{r}, t) = \sum_{n=1}^{N} c_n e^{-j(2\pi \Delta f_n t - \Delta k_n R)} \quad (15)$$

Where$n$isthenumberoffrequencycomponentsinthenarrowband, c_n isthecoefficientcorrespondingtoeachfrequency f_n , $\Delta f_n \ll f_c$, $\Delta k_n = 2\pi \Delta f_n / c$,thenequation(14)canberewrittenas:

$$p_{CE}(\vec{r}, t) = \sum_{n=1}^{N} c_n \frac{e^{-j(2\pi \Delta f_n t - \Delta k_n R + \Phi_t + \Phi_s)}}{R} (16)$$

InEq(16),Thephasecanbedividedintotwoparts:oneisthespatialcomplexenvelope($e^{j(\Delta k_n R - \Phi_s)}$)affectedbydistance;theotheristhetimecomplexenvelope($e^{-j(2\pi \Delta f_n t + \Phi_t)}$)affectedbytime.Rcontainsthepositioninformationofthesoundsourceandonlyaffectsthespatialcomplexenvelope.Sothecharacteristicsofthespatialco

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mplexenvelopeareaffectedbythewavenumberandfrequencyofthesoundsource,aswellasthecharacteristicsofthesoundsource.

4.Modulationmethodofspatialcomplexenvelope

WhenNAHtechnologyisusedtopredictthecomplexenvelopesoundfield,theconvolutionintegraloftheFouriertransformintimeandspaceisappliedatthesametime,soittakesarelativelylongoperationtime,andthereisalotofinformationthatisredundantinpracticalengineeringapplications.Forexample,intheidentificationandlocationofnoisesourcesorfaultdiagnosis,onlythepositioninformationandgeometricinformationofthesourcesoundfieldneedtobeobtained,andtheinformationiscompletelycontainedinthespaceenvelope.Soifwecanextractonlythespatialenvelopeofthetargetsoundfield,wecanreducetheamountofdatainthereconstructionprocess.

Lettheinitialphasebezero,andrewriteEq(13)asacombinationoffrequencies:

$$p(\vec{r},t)=\sum_{n=1}^{N}c_n\frac{e^{-j(2\pi f_n t+k_n R)}}{R} \quad (17)$$

ThespatialFouriertransformofthesoundpressureofanyfrequency$f_n$canbewrittenas:

$$p(x,y,z;f_n)=\frac{1}{4\pi^2}\int\int_{-\infty}^{\infty}P(k_x,k_y,z;f_n)\,e^{j(k_x x+k_y y)}dk_x dk_y \quad (18)$$

$p(x,y,z;f_n)$satisfiestheHelmholtzequationandissubstitutedintotheHelmholtzequation:

$$(\nabla^2+k^2)P(k_x,k_y,z;f_n)e^{j(k_x x+k_y y)}=0 \quad (19)$$

Forthesingle-frequencyfunction$P(k_x,k_y,z;f_n)$,itisonlyafunctionof$z$:

$$\frac{d^2}{dz}P(k_x,k_y,z;f_n)+(k_n^2-k_x^2-k_y^2)P(k_x,k_y,z;f_n)=0 \quad (20)$$

Accordingtothenormofdifferentialequationswithconstantcoefficientsinthefreespacewithoutreflection,thegeneralsolutionofEq(20)isexpressibleas:

$$P(k_x,k_y,z;f_n)=A(k_x,k_y,z;f_n)e^{jz\sqrt{k_n^2-k_x^2-k_y^2}} \quad (21)$$

Theequation(19)isderivedas：

$$(\nabla^2+k_n^2)P(k_x,k_y,z;f_n)e^{j(k_x x+k_y y)}=(\nabla^2+k_n^2)p(x,y,z;f_n) \quad (22)$$

SubstitutingEq(18)intoEq(22)andsubstitutingEq(21)intoEq(19),wecanobtaintheexpressionofthewavenumberspaceofthesoundpressurefieldatanyfrequencyf_n:

$$P(k_x,k_y,z;f_n)=j\pi\frac{e^{jz\sqrt{k_n^2-k_x^2-k_y^2}}}{\sqrt{k_n^2-k_x^2-k_y^2}}e^{-j(k_x x+k_y y)} \quad (23)$$

Theaboveformulaistheexpressionofthewavenumberspaceofthesoundsourcefieldofthepointsoundsourcewithspatialcomplexenvelopecorrespondingtoanypointfrequency.Bysimplifyingthemodelof$p_{CE}(\vec{r},t)$,therelationshipbetweenthespatialcomplexenvelope$p_{CE}(\vec{r},t)$andtheentiresoundpressurefieldisderivedinthewavenumberspace.Lettheinitialphasebezero;let$p_{CE}(\vec{r},t)$consistofonlytwofrequencycomponents f_m and $-f_m$,then $p_{CE}(\vec{r},t)$canbewrittenas:

$$p_{CE}(\vec{r},t)=\frac{e^{-jz(2\pi f_m t-k_m R)}}{R}+\frac{e^{-jz[2\pi(-f_m)t+(-k_m)R]}}{R} \quad (24)$$

Thesoundfield $p(\vec{r},t)$ consistsof $f_1=f_c+f_m$ and $f_2=f_c-f_m$ .Thespatialtwo-dimensionalFouriertransformofEq(24)isexpressedas

$$P_{CE}(k_x,k_y,z;f_m)=j\pi\frac{e^{jz\sqrt{k_m^2-k_x^2-k_y^2}}}{\sqrt{k_m^2-k_x^2-k_y^2}}e^{-j(k_x x+k_y y)} \quad (25)$$

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$$P_{CE}(k_x,k_y,z;-f_m)=-j\pi\frac{e^{jz\sqrt{(-k_m)^2-k_x^2-k_y^2}}}{\sqrt{(-k_m)^2-k_x^2-k_y^2}}e^{-j(k_xx+k_yy)} \quad (26)$$

Thetwo-dimensionalspatialFouriertransformofthee ntiresoundfield$p(\vec{r},t)$isobtainedbyEq(23):

$$P(k_x,k_y,z;f_1)=j\pi\frac{e^{jz\sqrt{k_1^2-k_x^2-k_y^2}}}{\sqrt{k_1^2-k_x^2-k_y^2}}e^{-j(\ \ _xx+k_yy)} \quad (27)$$

$$P(k_x,k_y,z;f_2)=j\pi\frac{e^{jz\sqrt{k_2^2-k_x^2-k_y^2}}}{\sqrt{k_2^2-k_x^2-k_y^2}}e^{-j(k_xx+k_yy)} \quad (28)$$

Thewavenumberspectrumofthespatialcomplexenvelopeandthewavenumberspectrumoftheentiresoundfield haveonlydifferentwavenumbers $k_1\to k_m$, $k_2\to -k_m$ onthesamegeometricinformation($e^{-j(k_xx+k_yy)}$). Thefrequencyshiftwiththetimecomplexmodulation,andthewavenumberchangeswiththefrequencyshift 。 Therefore,bymultiplyingtheEq(27)andEq(28)bythemodulationfactorMandconvertingthemintotheEq(25)andEq(26),amodulationmethodofthespatialcomplexenvelopecanbeobtained.

$$M_{k_1\to k_m}(k_x,k_y,z)=\frac{\sqrt{k_1^2-k_x^2-k_y^2}}{e^{jz\sqrt{k_1^2-k_x^2-k_y^2}}}\times\frac{e^{jz\sqrt{k_m^2-k_x^2-k_y^2}}}{\sqrt{k_m^2-k_x^2-k_y^2}} \quad (29)$$

$$M_{k_2\to k_m}(k_x,k_y,z)=-\frac{\sqrt{k_2^2-k_x^2-k_y^2}}{e^{jz\sqrt{k_2^2-k_x^2-k_y^2}}}\times\frac{e^{jz\sqrt{(-k_m)^2-k_x^2-k_y^2}}}{\sqrt{(-k_m)^2-k_x^2-k_y^2}} \quad (30)$$

5.Simulation

Amonopolesourceisusedtosimulatethesoundfieldwithaslowlyvaryingspatialenvelopeoscillationsoundfield. Let $Lx=Ly=4m$, $c=1500m/s$,thethreepointsourceswithslowlychangingspatialenvelopeoscillationbelocatedat $(x_{s1},y_{s1})=(0,1)$, $(x_{s2},y_{s2})=(-1,-1)$, $(x_{s3},y_{s3})=(1,-1)$ .Thecenterfrequencyofthenoisesourceis $f_c=2000Hz$, $\Delta f_m=20Hz$,Thesoundfieldreconstructiondistanceis $d_z=0.01m$,Thesoundfieldmeasuringdistanceis $z_H=0.02m$,thenumberofsamplingpoints $N=64$ .Usingnear-fieldacousticholographytoanalyzethesoundfieldreconstructionresultsforthesoundfieldwithspatialcomplexenvelope.

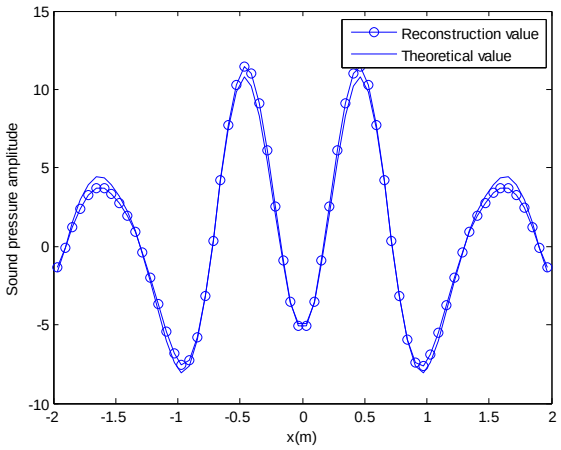

Fig.1.Thereconstructedsoundfieldbasedonnear-fieldacousticholography

AsshowninFig1 , Whenthesoundfieldreconstructiondistance $dz=0.01m$,thesoundfieldreconstructionsoundpressureamplitudeerrorissmall,andthesoundfieldcharacteristicscanbeaccuratelydescribed.Themeasurementdistance z_H andreconstructiondistance dz aregraduallyincrease

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d,thesoundfieldreconstructionaccuracyofthenearfield acousticholoramisfurtheranalyzed.Let $z_H = 0.1m$and$dz = 0.05m$:

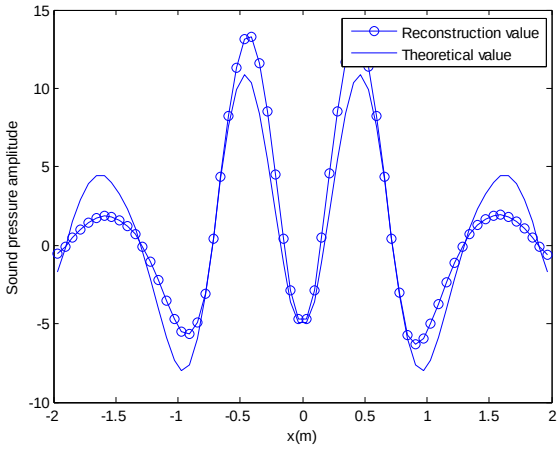

Fig.2.Thereconstructedsoundfieldbasedonnear-fielda coustichology raphy

Withtheincreaseofthereconstructiondistanceandthem easurementdistance,theaccuracyofthesoundfieldreco nstructiondecreasesfromtheFig2,anditserroris29.35% .Thisresultisconsistentwiththetheoryofnear-fieldacou stichology raphy.Thelargerthemeasurementdistance,th emorerepresentativecharacteristicsofthesoundsource canbeobtained.Thesmallertheevanescentwavecompo nent,thelargerthemeasurementdistance,thesmallerthe ratioofthesoundsourceareatothemeasurementsurface, andthelargerthewindingerrorcausedbytheconvolution calculation,sotheoverallaccuracyofthesoundfieldreco nstructionisreduced,butthesoundfieldreconstructionr esultscanreflectsthecharacteristicsofthesoundsource.

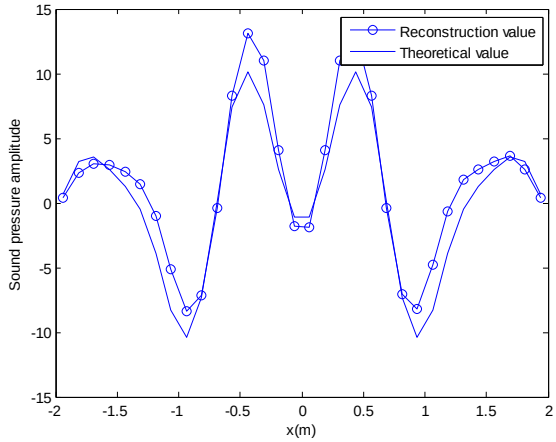

Fig.3.Thereconstructedsoundfieldbasedonnear-fielda coustichology raphy

Fig3showsthereconstructionresultswhenthenumberof samplingpoints N decreasesfrom64to32basedonthene ar-fieldacousticholographicalgorithmat $z_H = 0.1m$ and $z = 0.05m$ .Asthenumberofsamplingpointsdecreases,thea ccuracyofthesoundfieldreconstructiondecreases,butit doesnotaffectthejudgmentoftheentiresoundfieldradiat ioncharacteristics

Itcanbeseenfromthecomparisonofthecross-sectionald iagramsthatthenear-fieldacousticholographytechnolo gycanaccuratelyreconstructtheradiatedsoundfieldofar otatingmachineusingthespatialenvelopeinformationo fthesoundfieldandreflectstheradiationcharacteristicso fthesoundfield.However,whenonlythegeometricinfor mationofthesoundsourceneedstobeidentifiedandtheso undsourceislocated,themeasuredsoundpressurevalue canbemodulatedandonlytheenvelopeinformationofth esoundsourcecanbeextracted.Thefollowingfiguressh owthereconstructionresultsbeforeandafterthesoundfie ldmodulation.Aftermodulatingthesoundfield,thereco nstructionresulteliminatessomeredundantinformation ,anddirectlygivesthedistributionofthesoundfield,andt hesoundsourcelocalizationisaccurate.，

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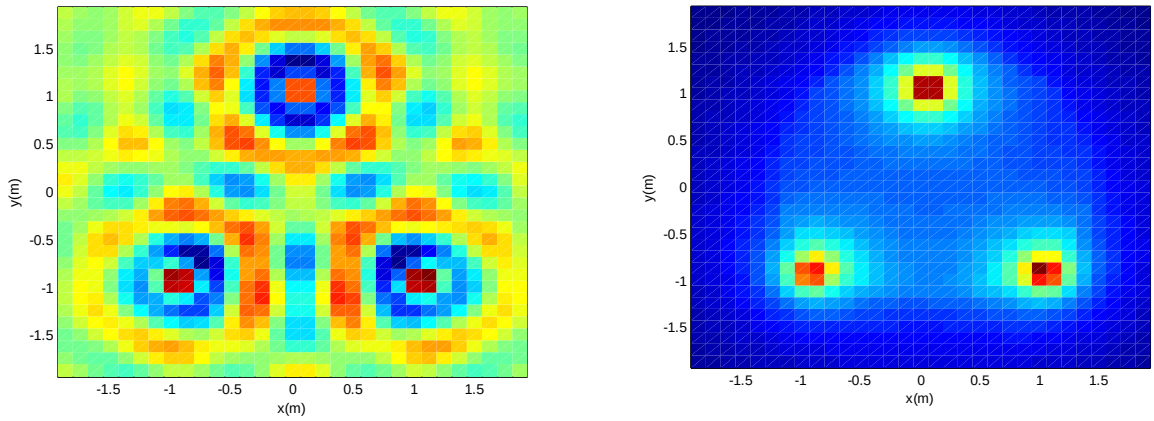
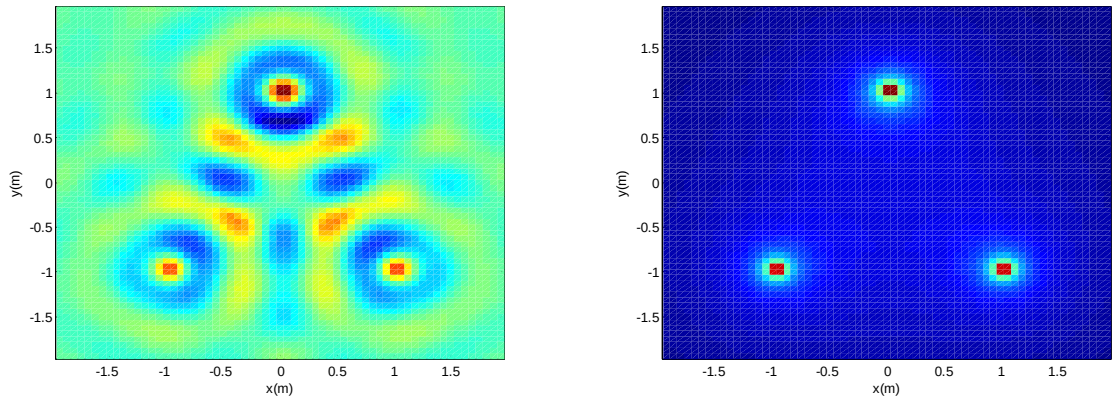


(a)non-modulation (b)modulation

Fig.4.Thereconstructiveresultsofnon-modulationandmodulation($N = 32$)



(a)non-modulation (b)modulation

Fig.5.Thereconstructiveresultsofnon-modulationandmodulation($N = 64$)

6Conclusions

Thispaperanalysesthesoundfieldmodelcontainingthespacecomplexenvelopegeneratedbytherotatingmechanicalstructure,andproposesamodulationmethodforthespacecomplexenvelope.Thenear-fieldacousticholographytechnologyisusedtoreconstructthesoundfieldofthemodulatedsoundfield,sothatthecharacteristicinformationofthesoundsourcecanbeobtainedmoreaccuratelyandeffectively,andtheinfluenceofredundantinformationonthecharacteristicsofthesoundsourcecanbereduced.Byanalysingthemeasurementdistance,thereconstructiondistanceandthenumberofsamplingpoints,thesoundfieldreconstructionaccuracyofthenear-fieldacoustichologramisdiscussed,andthefollowingconclusionsareobtained:(1)Fortheradiatedsoundfieldofrotatingmechanicalstructures,thenear-fieldacousticholographytechnologystillobtainshighsoundfieldreconstructionaccuracyundertheconditionoflargereconstructiondistance.Itdoesnotrequiremoresamplingpoints.Betterreconstructionaccuracycanbeobtainedevenwithfewersamplingpoints,soithascertainengineeringapplicationvalue;(2)Forthesoundfieldwithenveloperadiationpeculiartorotatingmechanicalstructures,envelopemodulationtechnologyisusedtoextracttheenvelopeinformationandperformsoundfieldreconstructiontoaccuratelyidentifythenumberandgeometricdistributionofsoundsources.Thistechnologynotonlyacceleratesthespeedofdataprocessing,butalsoensurestheaccuracyofsoundfieldreconstruction.

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