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APPLICATION OF PHASED ARRAY IN THE STUDY OF LINEAR CASCADE NOISE REDUCTION ON THE INDOOR TEST BED*

Weiyang Qiao[1], Liang Ji[2], Fan Tong[3], Kunbo Xu[4], and Weijie Chen[5]
School of Power and Energy, Northwestern Polytechnical University, Xi'an, 710072, China

ABSTRACT

A measurement technique with microphone array conventional beamforming for indoor linear cascade noise test is developing in NPU (Northwestern Polytechnical University of China) to quantify differences of sound source levels of linear cascade as a result of blade trailing edge modifications. The useful practical experience has been gained during this test. The special indoor microphones placement to avoid introducing ambiguities into sound source localization measurements in the hard-walled room test is firstly described in the paper. The reverberation time of test room is measured and is used to determine the range of direct-field of noise source acoustic radiation. A special microphones indoor placement method is used in the study to reduce the reflection from wall and to increase signal-to-noise ratio of the microphone array. The noise reduction potential of trailing edge serrations in NPU turbine linear cascade with 6 high-loaded LPT turbine blades is investigated experimentally with low cascade outlet Mach number. It is shown that turbulent boundary layer trailing edge noise is reduced in the low- to mid- frequency range and the largest noise reduction is about ~2 dB. This magnitude of cascade blade trailing edge noise reduction is obviously smaller than that of the isolated airfoil with using of serrated trailing edge.

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[1] Professor, Northwestern Polytechnical University, Xi'an, 710072, China, Qiaowy@nwpu.edu.cn.
[2] PhD Student, Northwestern Polytechnical University, Xi'an, 710072, China, cainiaojl@sina.com.
[3] PhD Student, Northwestern Polytechnical University, Xi'an, 710072, China, Tfan@mail.nwpu.edu.cn
[4] PhD Student, Northwestern Polytechnical University, Xi'an, 710072, China, Xukunbo@mail.nwpu.edu.cn.
[5] PhD Student, Northwestern Polytechnical University, Xi'an, 710072, China, Chenwj@mail.nwpu.edu.cn.

NOMENCLATURE

c	=	chord of blade, mm
c_x	=	axial chord of blade, mm
p	=	patch of cascade, mm
s	=	span of cascade, mm
β_1	=	cascade leading metal angle, deg
β_2	=	cascade trailing metal angle, deg
γ	=	cascade stagger angle, deg
ω	=	frequency, Hz
U_0	=	velocity of the mean flow, m/s
$2h$	=	root-to-tip distance for the saw tooth, mm
λ	=	wavelength of the serrations, mm
α	=	attack angle
SPL	=	sound pressure level, dB [ref 2×10^{-5} Pa]
b	=	beam width of the microphone array, m
r	=	distance between the array and the source, m
d	=	diameter of the microphone array, m
θ	=	source emission angle, degree

1 INTRODUCTION

The reduction of the turbulence broadband noise from the turbomachinery blade is nowadays an important industrial need and probably one of the most challenging issues in aero-acoustics.[1] The sources of turbomachinery broadband noise can be divided into Trailing Edge (TE) noise (airfoil self-noise) and turbulence cascade (or blade-row) interaction noise. TE noise results from the interaction between the turbulent boundary layers that grow on the blade and the sharp trailing edge. As the turbulent boundary layer is swept past the trailing edge, the sudden pressure release causes a distortion of eddies which eventually results in the production of sound as an elastic response of the medium to this excitation. A fully developed turbulent boundary layer involves a wide range of aerodynamic length scale, therefore the resulting sound is broadband. Among the turbomachinery broadband noise sources, Trailing Edge (TE) noise significantly contributes engine broadband noise. [1,2]

The reduction of turbulence broadband noise has been a matter of concern since the early days of aircraft manufacturing. The ability to fly silently of most owl species has long been a source of inspiration for finding solutions for quieter aircraft and turbomachinery.[3,4] Since the sharp trailing edge acts as a scattering enhancer, the reduction of broadband trailing edge noise through trailing edge modification appears to be a fruitful strategy in the global goal of reducing aircraft noise. Inspired from the ability to fly silently of the owl species, Howe (1991) first proposed the noise reduction concept using a serrated TE design.[5,6] Following Howe's encouraging theoretical work, many experimental studies assessed the acoustic benefit of serrated TE, and serrations reveal to be a robust noise reduction device since the reduction occurs for all airfoils.

However, the most researches of the serrated TE were on the self-noise reduction of the isolated or the wind turbine blades, and only few studies were on the turbomachiner cascade noise reduction. In 2011, Finez et al first published the broadband self-noise reduction of a linear cascade with trailing edge serrations.[7,8] They used a linear cascade with seven cambered airfoils to experimentally measure turbulent boundary layer-trailing edge noise in the downstream direction. Based on the detailed flow filed measurements in the near wake of the center blade using high speed particle image velocimetry and detailed aerodynamic performances measurements using pressure probes, Finez et al explain possible aerodynamic mechanisms of the noise reduction process.

But at the same time, Finez et al only used simple acoustic far field measurement with two microphones located 2 m away from the center of the cascade to determine the noise reduction of linear cascade with serrated trailing edge. It is well-known that there are multi-sources to radiate noise from cascade wind tunnel which include the jet noise of cascade exit, the cascade inflow noise, as well as the blade leading edge noise, and these sources radiate the broadband noise with the same frequency range as that of the trailing edge noise. Consequently, it would be precise and appropriate for using the noise source localization to determine the noise reduction of linear cascade with serrated trailing edge.

Acoustic beamforming with microphone phased-arrays is a powerful method to investigate the flow noise emission.[9] This technique has been largely used in aeronautics to investigate and characterise aerodynamic noise.[9,10,11] Beamfoming has made it possible to locate specific acoustic sources like trailing edge noise and leading edge noise and thus contributed to reduce the airfoil, blade, as well as turbomachinery noise. The present paper concerns the application of beamforming to linear cascade noise reduction with serrated trailing edge. In this study, phased microphone arrays were applied to localize the linear cascade blade trailing edge noise sources with special trailing edge structure. The radiated sound from blades with serrated trailing edge and the blades with routine straight edge in an open cascade wind tunnel was measured by a linear acoustic array with 31 un-equally distributed microphones in a range of 2.4 m. And the array is located the 0.35 m from the cascade exhaust. The data of the microphone array was used to compare the noise levels from different blade trailing edge of the cascade by focusing the array at the plane of trailing edge of the cascade. It is well-known that the DAMAS algorithm, which was first introduced by Brooks and Humphreys[12] in 2004, is an effective data reduction method to increase the resolution of acoustic arrays and eliminating disturbing side-lobe effects. This DAMAS approach was used to analyze the array data in the present paper. The source patterns and strengths obtained by beamforming for the cascade were illustrated and discussed in present paper.

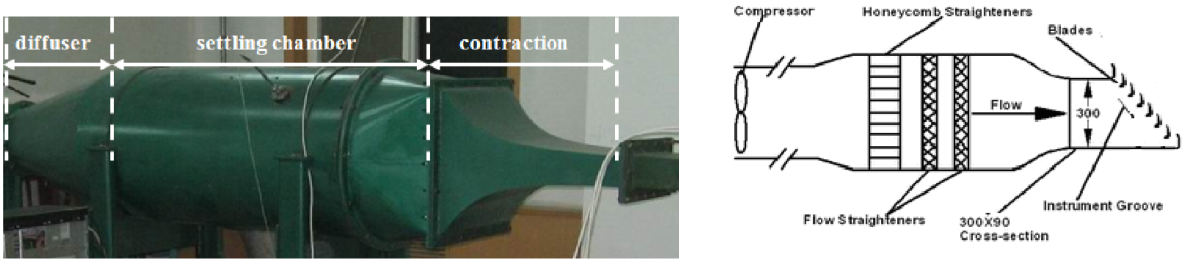
2 EXPERIMENTAL SET-UP

The experiment was carried out in the low speed turbine cascade indoor test bed (in the Northwestern Polytechnical University (NPU) of China) on the high-lift (Zweifel lift coefficient is 1.217) low-pressure turbine (LPT) profile with and without serrated trailing edges.

2.1 Turbine Cascade Test Bed

The linear cascade experiment is conducted in the indoor wind tunnel test bed (Fig. 1). The cascade wind tunnel can be broken up into two major sections: the upstream section and the test section. The upstream section consists of the centrifugal fan, the diffuser, the settling screens and the contraction. Flow is supplied to the tunnel through a centrifugal fan which is powered by a 20 Kw AC motor. After passing through the fan, the flow is slowed down through a diffuser before entering the settling chamber. The total length of the diffuser and the settling chamber is about 5 m while the expansion ratio from the exit of the fan to the settling chamber is 1:5.75. Before exiting the settling chamber and entering the contraction, the flow passes through flow conditioning screens to reduce the turbulence levels and swirling. The contraction, with a contraction ratio of 1:8.22 directs the flow into the inlet of the test section (Fig. 1(a)).

The inlet of cascade is a 0.3m × 0.09 m rectangular channel. Air is supplied by wind tunnel at Mach numbers ranging up to 0.30 in the inlet of the cascade with the Reynolds numbers based on blade chord ranging from 0.5×10^5 to 5.5×10^5 at the free-stream turbulence intensity about 1 %. The airflow passes through the cascade and discharge to outside air through the flow collector apart from but direct to the cascade. The blade trailing edges are exposed to the indoor space which is downstream cascade (Fig.1 (b)).



(a) *(b)*

Fig.1 Picture and sketch of the indoor cascade wind tunnel.

2.2 Linear Cascade with and without Serrated Trailing Edge

The linear cascade shown on Fig. 1(b) is made of 6 high-loaded (Zweifel lift coefficient is 1.217) low-pressure turbine (LPT) profile with and without serrated trailing edges. This airfoil is designed by NPU for the multi-stages low pressure turbine (LPT) of the civil high bypass turbofan. The blade chord is c = 50 mm and their span is L = 90 mm, the pitch is p = 47.5 mm. Consequently the solidity is $\sigma = c/p = 1.05$. The cascade orientation is defined by two angles shown on Fig. 2(a), the leading metal angle $\beta 1 = 32.7$, trailing metal angle $\beta 2 = 62.3$. The cascade stagger angle is $\gamma = 30.7$, and the attack angle $\alpha = 0$.

(a) *(b)*

Fig.2 Picture and sketch of the cascade test rig.

Two serrated trailing edges which are respectively with the sawtooth of λ/h = 0.5 and 1.0 , the ratio of wavelength of serrations λ (2 mm and 4mm) to their amplitude h ($2h$ = 8 mm) , were tested in present study. Fig. 2b gives the pictures of blade with and without trailing edge saw-tooth.

3 PHASED ARRAY MEASUREMENT IN INDOOR TEST BED

3.1 Indoor Microphones Placement

Despite the fact that microphone measurement is complicated by reflections of the sound waves in wind tunnel or indoor test beds, the applications of more and more microphone arrays in wind tunnels and test room have proven their ability to quantify differences in sound source levels as a result of model modifications, using the Conventional Beamforming technique.[9~15] This paper is also focus on the quantification of the differences in sound source levels as a result of cascade blade trailing edge modifications with serrations, so, the conventional beamforming of microphone array is used in the study. However, it should be firstly noted that sound source localization of the conventional beamforming is based on the incident sound wave, and ill-suited placement of microphone array may introduce ambiguities into sound source localization measurements in the hard-walled room test. When using conventional beamforming in indoor test bed, the following problems should been firstly taken into account and been determined.

(1) Direct field and reverberant field

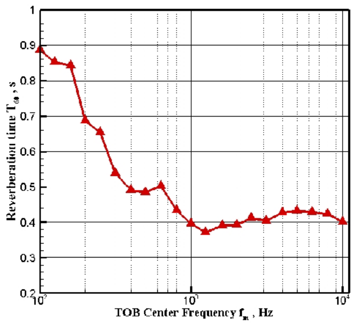
The microphone should be put in the direct-field or free-field to estimate the acoustic radiation of noise source. As indicated by Soderman and Allen[16], the direct field is the region near the source where the source levels are strong enough to dominate the reverberant sound caused by any reflections. In the acoustic field which there exist sound reflection such as in hard-walled test room, the direct field could be determined by the reverberant radius $r_{H,}$ it defines the distance from a source where the pressure level of the direct sound and the diffuse noise field are equal. The following equation defines r_H for an omnidirectional source and microphone [17]:

$$r_H = 0.057\sqrt{V/T_{60}} \tag{1}$$

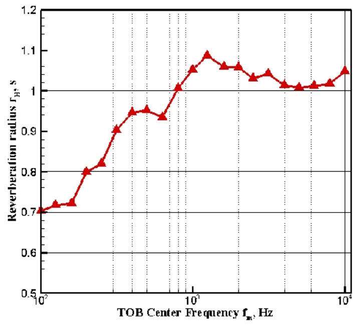
where r_H in m is a function of the room volume V in m³ and the reverberation time T_{60} in s. The signal of a microphone positioned at a distance from the sound source smaller than the reverberant radius is dominated by the sound source. Microphones at larger distances, however, are dominated by the diffuse field or background noise.

The reverberation time T_{60} is a measure to describe the absorption of acoustic energy in an enclosure. It is the time during which the sound pressure level drops by 60 dB after a sound source was suddenly turned off.[17] A strong absorption or a short reverberation time causes low background noise levels and increases the acoustic reverberant radius r_H. The method as suggested by Böhning et al[17] was used in this study to measure the reverberation time of the cascade test bed room with an omni-directional sound source. A noise signal is produced by loudspeaker and suddenly is turned off, from the signal of the microphone, the reverberation time T_{60} was calculated. Figure 3 shows the results for the one-third octave bands between 100 Hz and 10 kHz.

From Fig. 3(a), it could be seen that the reverberation time for frequencies higher than 500 Hz is below 0.5 s. The corresponding reverberation radius was calculated with an estimated volume of the room V = 8.4 × 6 × 2.68 m and is plotted as a function of frequency in figure 3b. It could be seen that the reverberant radius is in 0.7 m to 1.1 m. It can be concluded that when the distances of all microphones of array to the source is smaller than 0.7 m, the array signals are located in the direct field in the frequency range of 100 Hz-10000 Hz.



(a)



(b)

Fig.3 Reverberation time and reverberation radius in the test bed as function of 1/3-octave band centre frequencies.

(2) Near-field effects and far-field measurement

Microphones too close to the sound source also cause errors.[16,17] A microphone placed in the acoustic near-field, could suffer significantly from pressure fluctuations which do not propagate as sound, and the signals of the microphone will not be representative of the sound propagating to far-field, which is what we are usually trying to simulate. To avoid this effect, it is generally found that the source-to-microphone distance should be at least half of one acoustic wave length(keep the microphone in the acoustic far-field, beyond the hydrodynamic fluctuation close to the source.) and two source dimensions(keep the microphone in the geometrical far-field).[16] In the far-field, the acoustic pressure decays as 1/r (where r is the distance measured from source center), and according this relation to build up steering vector for the conventional beamforming.

The sound source of this paper is on the trailing edge, the dimension of this source is limited in 0.0475 m of one pitch of the cascade. So, if the microphones is placed at 0.35 m from trailing edge of cascade in the direct field of the cascade test room, signals of the microphone can be expected to be in the geometrical far-field ($0.35 >> 2\times 0.0475$), and expected to be in the acoustic far-field for frequencies $f > 1000$ Hz (the half of the acoustic wavelength is about 0.17 m). This frequency range would be used to investigate the noise reduction of trailing edge with serration configuration.

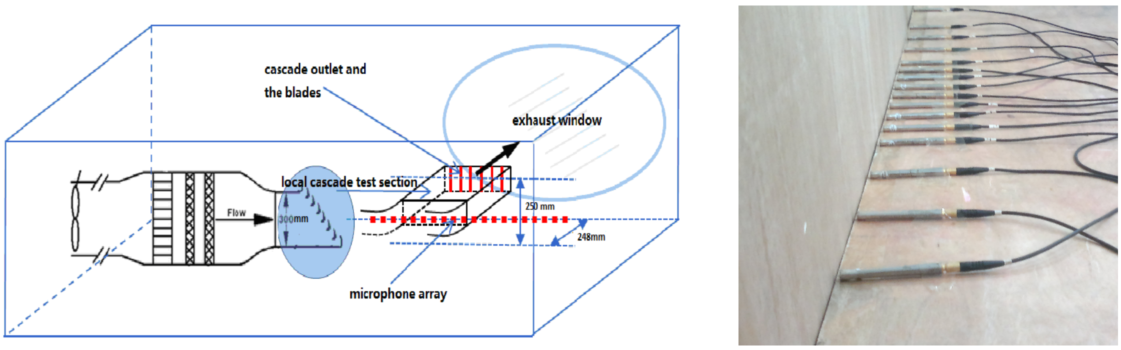
(3) Placement at the inner edge of the room

In order to reduce reflection from the wall of test room and to increase signal-to-noise ratio of the microphone array, a special microphones placement methods which proposed firstly by Siller et al was used in this study.[17,18] To deduce free-field noise levels from engine tests in semi-reverberant test cells with conventional beamforming, Siller et al in DLR developed a novel indoor microphone array, which the microphones are placed along the inner edge of the room between the floor and the adjacent wall to reduce the reflection from wall. The microphone along inner edge of the room is only subject to reflections from the opposite wall and the roof of the test room and not subject to reflection from adjacent wall.

According to the position of tested cascade in the test room, the linear array with unequal spacing 31 microphones was laid along the inner edge which is opposite to the cascade outlet in the room in this study as shown in Fig. 4(a). The array is underneath the center of the blade about 0.25 m, and downstream the outlet of cascade about 0.248 m, and the center of the array is placed underneath the center axes of the cascade outflow. The distance from the center of array to the central blade of cascade is about 0.35 m.

3.2 Microphone Array

An unequal spacing linear microphone array with 32 microphones (Fig. 4(b)) was used to localize trailing edge noise source. As indicated above, the cascade blade trailing edges are exposed to the indoor space which is downstream cascade. The array was placed downstream and underneath the cascade outlet (see Fig. 4(a)), so that the microphone array could directly focus on (the microphones of the array could all see the trailing edge of the cascade blades) the trailing edge of each blade in the cascade.



(a) *(b)*

Fig.4 Schematic diagrams of experimental setup. (a): Microphones placement in indoor cascade test bed; (b): Picture of the microphone array.

The ¼ inch capacitive microphones produced by BSWA Company are used. Frequency range of this type microphone is from 20 Hz to 20 kHz in free field, and sound pressure levels up to 168 dB. The sensitivity is 5 mV/Pa. The microphone has an operating temperature range of –50 to +110 degree Celsius, and with a main ambient temperature coefficient of 0.01 dB/K and a main ambient pressure coefficient of -10^{-5} dB/Pa. The ¼ inch measuring microphone preamplifier is a high-impedance transducer for condenser measuring microphone cartridges. It permits a wide-band measurements and sound level measurements with a dynamic range from 17 up to 168 dB. Its frequency range is from 1 Hz to 1 MHz. The microphone preamplifiers were connected to the BBM data acquisition system. The largest sampling rate of the BBM system was 102.4 KHz. All microphone signals were simultaneously sampled with an AD conversion of 16-bit at a sampling frequency of 32768 Hz. The recording time for one measurement was 10 s. The calibration constants of microphones were obtained by using a 1000 Hz single frequency standard sound source before the measurement started. All microphones were mounted with their preamplifiers lying on top of the plate with a grazing incidence of the microphone diaphragm (as shown in Fig. 4(b)).

3.3 The Beamforming of Microphone Array

As indicated above, conventional beamforming is used in this study to quantify differences of trailing edge sound source levels with serration. The performance of a microphone array is the beam pattern, which is the spatial response of the array beam forming to a mono-pole wave. An array beam pattern comprises a main lobe or beam and a number of smaller side lobes on either side of the main beam. The width b of the main lobe at 3 dB below the peak decides the spatial resolution of the array and it puts a limit on the lowest frequency of the array analysis, where two adjacent sources can be resolved. The beam width b of the array is proportional to the wavelength λ, the distance between the array and the source r and inversely proportional to the diameter of the array d and the emission angle θ:

$$b \propto \frac{\lambda r}{d \sin^2 \theta} \tag{2}$$

As shown in Fig. 4, the emission angle is about 45 degree and the distance r is 0.35 m. Based on the cascade patch which is the sound source space resolving of the array, the linear array has been designed. The length of the linear array was 2.4 m, the max space between two adjacent microphones was 0.2 m and the minimum space was 0.05 m. The array analysis was carried out in the frequency domain with the Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) method. DAMAS which was developed by Brooks and Humphreys (2004) has been quantitatively validated using archival data from a variety of prior high-lift airframe component noise studies. In this study, the cross-spectral density matrix was calculated from the measured signals using a Hanning window with a block-size of $N = 8192$ samples and a 50% overlap. This resulted in a frequency resolution of 4 Hz.

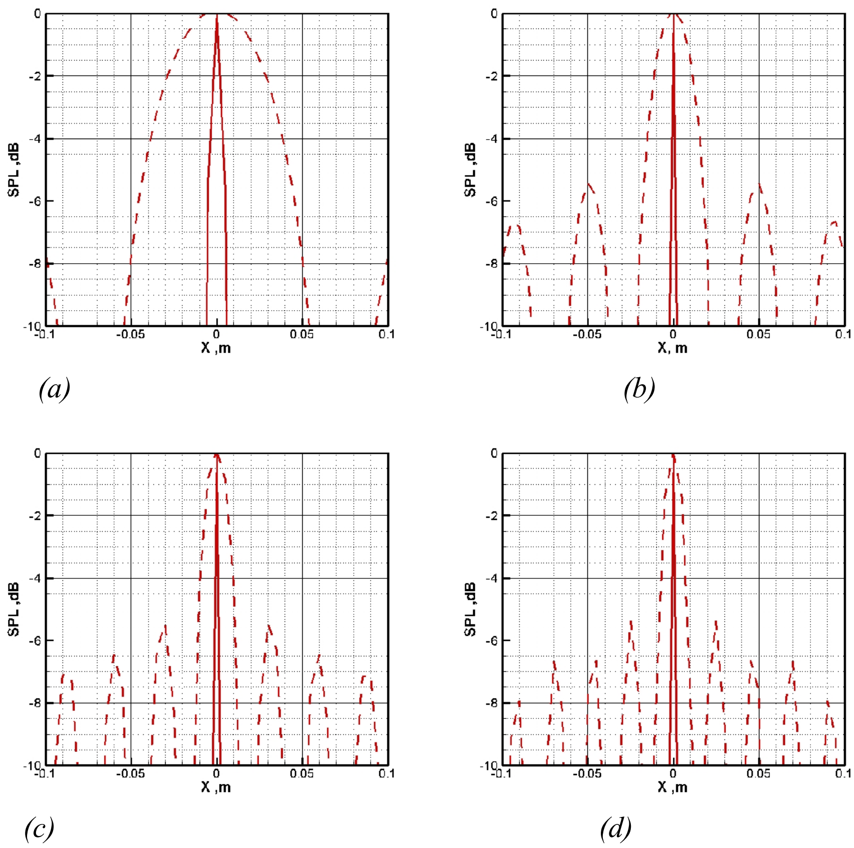


Fig.5 Array patterns of the linear array as a function of the distance x. With a source locating at r= 0.35 m, (a), (b), (c), and (d): 1/3-octave band with center frequency of 1600 Hz, 4000Hz, 6300Hz and 8000 Hz. (Dashed line: conventional beamforming results; Solid line: DAMAS results, 1000 iterations)

The point-spread function of this linear microphone array for four different frequencies is shown in Fig. 5. The x coordinate illustrates the noise source position and the y coordinate is sound pressure level (SPL). This function describes the map which is produced by a single point source and gives information about the spatial resolution and the main- to side-lobe ratio of the microphone array. It can be seen that the beam-width *b* of the array, which is defined as the width of the main lobe at 3 dB below the peak, is approximately 0.07 m at f = 1600 Hz and 0.012 m at f = 8000 Hz from the conventional beamforming results. However, when we used the DAMAS method to deal with the conventional beamforming results further, the side-lobes have been disappeared and the spatial resolution is much higher and is suitable to identify cascade trailing edge noise source. The scanning distance Δx in Fig. 5 is 0.005 m during the DAMAS process.

4 BEAMFORMING RESULTS

4.1 Measurement Scheme

The noise radiation from cascade blades with and without serrated trailing edge was measured separately on the flow velocity of 31 m/s, 44 m/s and 50 m/s at the exit of the turbine cascade, and the corresponding chord-based Reynolds number is 106,000, 151,000 and 171,000. The angle of cascade attack α is set to 0°. Because the Mach number of the main flow is low, less than 0.2, the refraction of the acoustic wave by shear layer can be neglected.

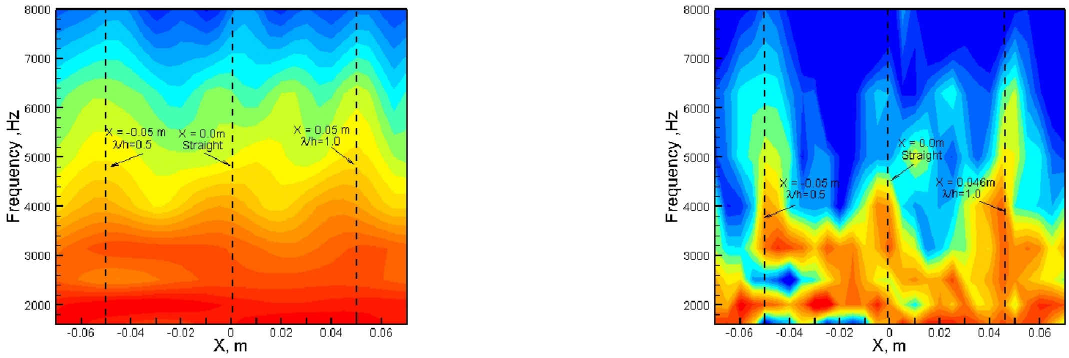
In order to accurately quantify differences in sound source levels as a result of cascade blade trailing edge modifications, the blades with and without serrated trailing edge were synchronously tested in the cascade. As shown in Fig. 4(a), the 3 blades in the center region of cascade were as the tested blade in the cascade of 6 blades, which 1 blade is normal straight trailing edge blade (in the center of cascade) and 2 blades on both sides of the normal blade are serrated trailing edge blades which are respectively with the sawtooth of λ/h = 0.5 and 1.0 , the ratio of wavelength of serrations λ (2 mm and 4 mm) to their amplitude h ($2h$ = 8 mm) , as shown in Fig. 2(b).

It should be indicated that the aerodynamic performance of the cascade will be changed some little when the blade trailing edge is serrated. The present study is focus on the acoustic performance of the blade trailing edge, the possible little effect of the changing of the aerodynamic performance on the trailing edge sound radiation is neglected in the study.

4.2 Acoustic Source Locations as a Function of Frequency

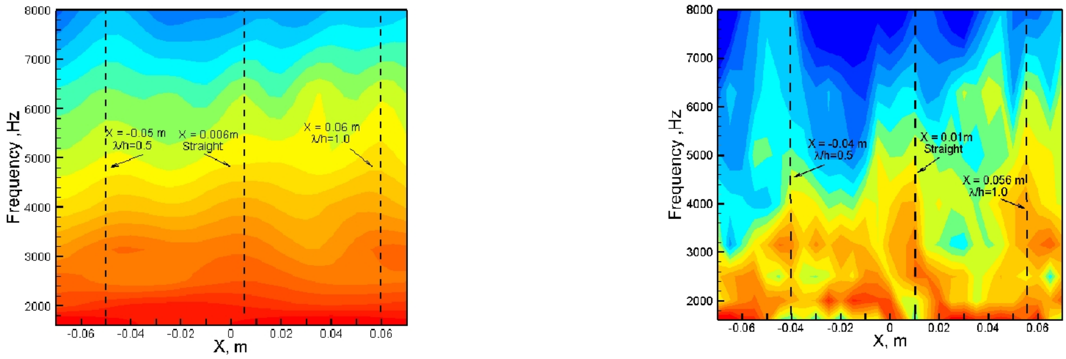
To identify the trailing edge noise and analysis the noise reduction mechanism behind the serrated trailing edge, phased microphone array beam-forming was used to discriminate acoustic power emanating from trailing-edge noise sources. The scanning region at intersectant line of the central plane of the cascade in span direction with the cascade outlet plane was in the region 3 patch of the cascade as shown in Fig. 4(a) and the space of the grid points was 0.01 m.

Figure 6 to 8 show the conventional beamforming and DAMAS results along scanning line between 1.6 kHz and 8 kHz for the normal and serrated blades. The flow velocity is 31 m/s in Fig. 6, 44 m/s in Fig. 7 and 50 m/s in Fig. 8. The abscissa is the coordinate located on the center line of the cascade patch direction which represents the distribution of the noise sources and the ordinate is the frequency ranges from 1.6 kHz to 8 kHz. Because the beam width *b* of the array is too large to identify the cascade blade trailing edge noise source (the cascade patch is 0.0475m) below the frequency of 1600Hz, the beamforming results in this paper are focus on the frequency range of 1600Hz to 8000Hz.



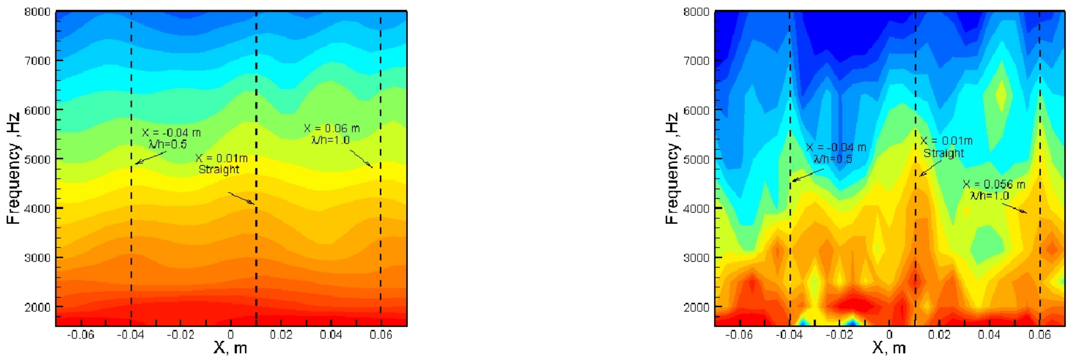
(a) (b)

Fig.6 Source distributions in a 31 m/s flow. (a): Beamforming results; (b): DAMAS results, 1000 iterations.



(a) (b)

Fig. 7 Source distributions in a 44 m/s flow. (a): Beamforming results; (b): DAMAS results, 1000 iterations.



(a) (b)

Fig.8 Source distributions in a 50 m/s flow. (a): Beamforming results; (b): DAMAS results, 1000 iterations.

It could be seen from Fig. 6 to Fig. 8 that, the array data reduction with DAMAS improved the sound source identifying obviously compared to the conventional beamforming. The trailing edge noise sources could be localized in the frequency range of 1.6 kHz-8 kHz with the using of the data reduction method of the DAMAS. From Fig. 6 to Fig. 8, it can be seen that three main sources from trailing edge of the 3 blades are spaced with cascade patch. The trailing edge noise is visibly reduced with the serrated trailing edge. The noise reduction of the serrated trailing edge blades with the sawtooth of λ/h =0.5 is more notable than that of the serrated trailing edge with the sawtooth of λ/h = 1.0. It could be also seen that the sound pressure level of the noise sources decrease with the increase of the frequency.

In order to quantitatively analyze the noise reduction of the serrated trailing edge, Fig. 9 shows the comparison of the total sound pressure level of the trailing edge noise source in the 1/3-octave band center frequency range from 1600 Hz to 8000 Hz, and Fig. 10 shows the comparison of the sound pressure level of trailing edge noise source in the 1/3-octave band with center frequency of 2000 Hz, 4000 Hz, 6300 Hz and 8000 Hz. In these figures, the red line is the beamforming results for flow velocity of 31 m/s, blue line is the results for flow velocity of 44 m/s, and green line is the results for flow velocity of 50 m/s. The trailing edge source of the blade without serration is marked with symbol ellipse, the trailing edge source of the blade with sawtooth of λ/h = 0.5 is marked with symbol circle, and the trailing edge source of the blade with sawtooth of λ/h = 1.0 is marked with symbol square. These results show that the blade trailing edge noise in the cascade is identified clearly with the microphone array. The sound pressure level of the trailing edge noise is obviously increased with the increase of the flow velocity. The results in Fig. 9 indicate that the using of serrated trailing edge with sawtooth of λ/h = 0.5 could obviously reduce the total sound pressure level in the frequency range of 1600 Hz to 8000 Hz. However, the reduction of total sound pressure level is not visible with the using of serrated trailing edge with sawtooth of λ/h = 1.0.

Figure 9 and 10 also show that the position of trailing edge noise source, or the position of largest sound pressure level presenting itself in the trailing edge flow, moves with the variation of the cascade flow velocity. This is easily understood considering the fact that the trailing edge wake flow structure is changed with the change of the flow velocity due to the variation of the blade surface boundary layer thickness and the variation of the center position of blade wake.

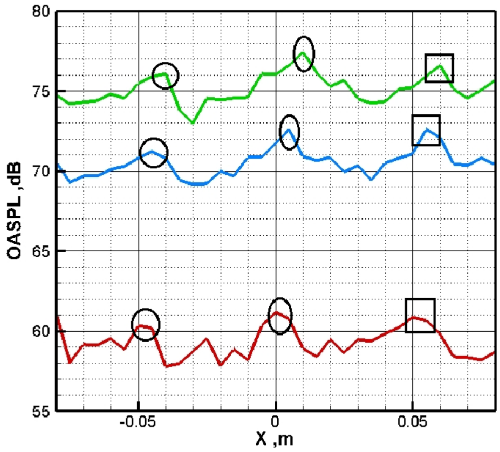


Fig.9 Total sound pressure level distribution of sources(using DAMAS method). Red: flow velocity of 31 m/s; Blue: flow velocity of 44 m/s; Green: flow velocity of 50 m/s. The frequency range of the total sound pressure level is from 1600 Hz to 8000 Hz. Ellipse: straight edge blade; Cirlce: serrated edge blade with λ/h =0.5; Square: serrated edge blade with λ/h =1.0.

Figure 10 shows that, the effect of the serrated edge on the noise radiation of trailing edge changes with the variation of noise radiation frequency. In low frequency, the trailing edge noise is reduced with the using of serrated edge. However, in some high frequency, the trailing edge noise is increased with the using of serrated edge. It could also be seen from Fig. 10 that there are some other special strong noise sources between the blades of the cascade (see Fig. 10(c)). This special tone noise is considered from cascade tunnel flow or from the centrifugal fan.

4.3 Noise Reduction Assessment

The beamforming analysis can provide the source maps and also the frequency spectra for specific point. Figure 11 to 13 show the comparison of the 1/3-octave band spectra of the TE noise of the blade with and without the sawtooth in the frequency range of 1600 Hz to 8000 Hz. In these figures, the red line is the spectra of the TE noise of the baseline blade (straight trailing edge blade), green line is the spectra of the TE noise of the blade with the sawtooth of $\lambda/h = 0.5$, and blue line is the spectra of the TE noise of the blade with the sawtooth of $\lambda/h = 1.0$.

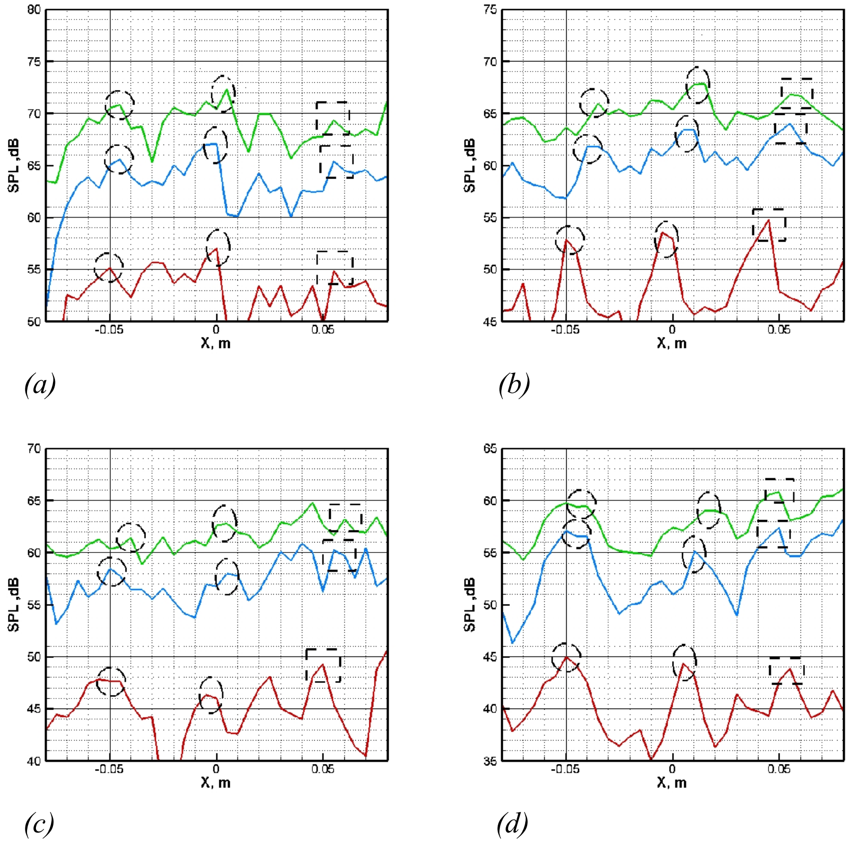
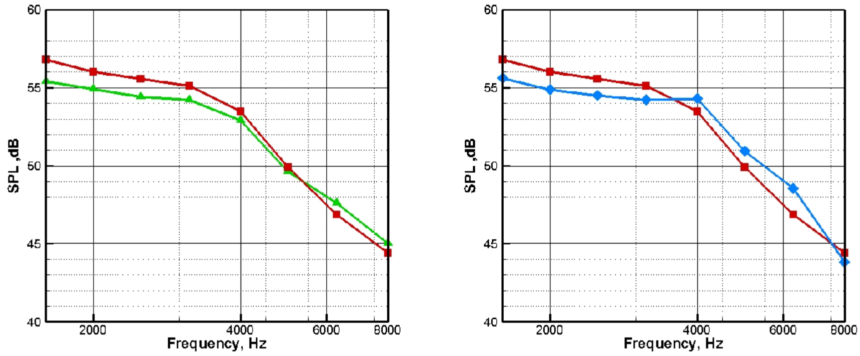


Fig.10 Sound pressure level distribution of the sources(using DAMAS method) on the 1/3-octave band with center frequency of 2000 Hz(a), 4000 Hz(b), 6300 Hz(c) and 8000 Hz(d). Red: flow velocity of 31 m/s; Blue: flow velocity of 44 m/s; Green: flow velocity of 50 m/s. Ellipse: straight edge blade; Cirlce: serrated edge blade with λ/h =0.5; Square: serrated edge blade with λ/h =1.0.

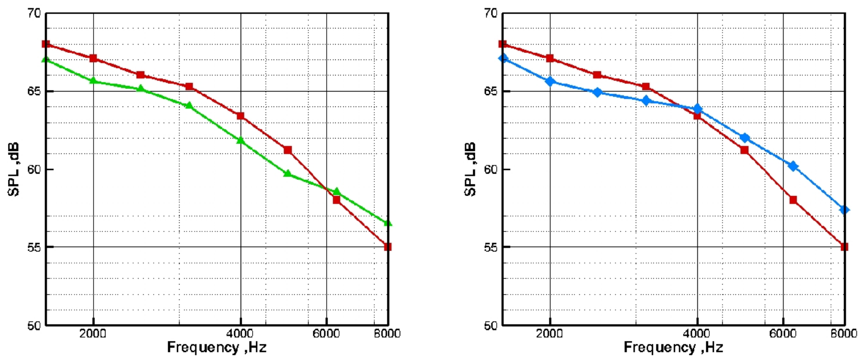
It could be seen from Fig. 11 that for the cascade exit flow velocity of 31 m/s, with the using of serrated trailing edge of $\lambda/h = 0.5$, the cascade blade trailing edge noise is reduced effectively about 0.5 ~ 1.5 dB in the frequency range of 1600 Hz-5000 Hz, and is increased less than 1 dB in the frequency range of 5000 Hz-8000 Hz. However, with the using of serrated trailing edge of $\lambda/h = 1.0$, the cascade blade trailing edge noise is reduced effectively about 1.0 dB in the frequency range of 1000 Hz-3500 Hz, and is increased about 1.0 ~ 1.5dB in the frequency range of 3500 Hz-8000 Hz.

Figure 12 and 13 show that with the increase of the cascade flow velocity, the frequency range of the noise reduction with the using of serrated trailing edge is increased. It could be seen from Fig. 12(a) and Fig. 13(a), that, with the using of serrated trailing edge of λ/h = 0.5, the frequency range of the cascade blade trailing edge noise effective reduction is from 1600 Hz to 6000 Hz for the cascade outlet flow speed of 44 m/s, and the frequency range is from 1600 Hz to 7500 Hz for the cascade outlet flow speed of 50 m/s. The largest noise reduction is about 1.5 dB for the cascade working at the exit flow velocity of 44 m/s in the frequency range of 1600 Hz to 6000 Hz, and the largest noise reduction is about 2.2 dB for the cascade working at the exit flow velocity of 50 m/s in the frequency range from 1600 Hz to 7500 Hz.



(a) *(b)*

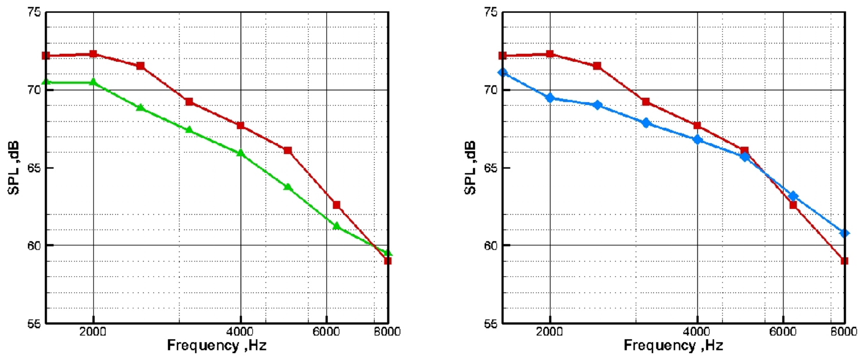
Fig.11 Comparison between the 1/3-octave band spectra with center frequency ranges from 1600 Hz to 8000 Hz. U0 = 31 m/s. Red: noise source of baseline blade with straight TE; Green: noise source of serrated edge blade with λ/h = 0.5; Blue: noise source of serrated edge blade with λ/h = 1.0.



(a) *(b)*

Fig.12 Comparison between the 1/3-octave band spectra with center frequency ranges from 1600 Hz to 8000 Hz. U0 = 44 m/s. Red: noise source of baseline blade with straight TE; Green: noise source of serrated edge blade with λ/h = 0.5; Blue: noise source of serrated edge blade with λ/h = 1.0.

A similar variation trend of the noise reduction with the change of flow velocity for the using of serrated trailing edge of λ/h = 1.0 could be seen from Fig 12(b) and 13(b). With the increase of cascade exit flow velocity, the frequency range of the cascade blade trailing edge noise effective reduction and the largest noise reduction are all increase. The valid frequency ranges for trailing edge noise reduction is from 1600 Hz to 3500 Hz in 31 m/s flow, from 1600 Hz to 3700 Hz in 44 m/s flow and from 1600 Hz to 5500Hz in 50 m/s flow. In the above frequency range, the largest noise reduction of sound pressure level is about 1.0 ~ 2.5 dB in the test flow speed range. However, the serrated trailing edge of λ/h = 0.5 is more effective than the serrated trailing edge of λ/h = 1.0 for the cascade trailing edge noise reduction. And in the high frequency range, the trailing edge noise with the sawtooth of λ/h = 1.0 is increased more than that of the trailing edge noise with the sawtooth of λ/h = 0.5. Compared with the isolated airfoil noise reduction results,[19] the magnitude of cascade blades trailing edge noise reduction with the using serrated trailing edge are obvious smaller.



(a) *(b)*

Fig.13 Comparison between the 1/3-octave band spectra with center frequency ranges from 1600 Hz to 8000 Hz. U_0 = 50 m/s. Red: noise source of baseline blade with straight TE; Green: noise source of serrated edge blade with λ/h = 0.5; Blue: noise source of serrated edge blade with λ/h = 1.0.

5 CONCLUSION

A measurement technique with microphone array conventional beamforming in indoor cascade test bed have been conducted on NPU linear turbine cascade with 6 high-loaded blades, and useful practical experience has been gained during the test. Turbulent boundary layer trailing edge noise has been measured in the downstream direction for flow velocities ranging from 31m/s up to 50 m/s. Noise reduction on a broadband frequency range was quantified in sound source levels as a result of trailing edge serration modification.

According to the experimental results, some conclusions can be drawn below.

(1) The present test results show that trailing edge noise source could be identified clearly with the using of special designed linear microphone array in indoor test room. The focus of the microphone array which is on the trailing edge noise radiation could be used to investigate the cascade noise reduction with the serrated trailing edge.

(2) The cascade blade trailing edge noise could be effectively reduced with the using of serrated trailing edge, and the magnitude and frequency range of blade trailing edge noise reduction are changed with the increase of main flow velocity. It is noted that the serrated trailing edge with the sawtooth of λ/h = 0.5 is more effective to reduce cascade trailing edge noise than the serrated trailing edge with the sawtooth of λ/h = 1.0 in the flow velocity range of the test. However, the magnitude of cascade blade trailing edge noise reduction is obviously smaller than that of the isolated airfoil with using of serrated trailing edge.

(3) For the serrated trailing edge with the sawtooth of λ/h = 0.5, the valid frequency ranges for trailing edge noise reduction is from 1600 Hz to 5000 Hz in 31 m/s flow, from 1600 Hz to 6000 Hz in 44 m/s flow and from 1600 Hz to 7500Hz in 50 m/s flow. In the above frequency

range, the largest noise reduction of sound pressure level is about 1.0~2.2 dB in the test flow speed range.

(4) For the serrated trailing edge with the sawtooth of λ/h = 1.0, the valid frequency ranges for trailing edge noise reduction is from 1600 Hz to 3500 Hz in 31 m/s flow, from 1600 Hz to 3700 Hz in 44 m/s flow and from 1600 Hz to 5500Hz in 50 m/s flow. In the above frequency range, the largest noise reduction of sound pressure level is about 1.0~2.5 dB in the test flow speed range. And in the high frequency range, the trailing edge noise with the sawtooth of λ/h = 1.0 is increased more than that of the trailing edge noise with the sawtooth of λ/h = 0.5.

(5) It should be noted that the cascade blade trailing edge noise could be increased with the using of serrated trailing edge in some frequency range.

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