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Experimental Study on BTI Broadband Noise Reduction with Wavy Leading Edge for Sweep Blade*

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ABSTRACT

Experimental studies are performed to investigate the Blade-Turbulence Interaction (BTI) noise reduction of a sweep blade with wavy leading-edge (WLE) configuration. The noise radiation from the sweep blade leading-edge is generated by the interaction of the blade and incoming anisotropic turbulence which is produced by a rod whose wake impinges onto the downstream NACA0012 airfoil. A linear array of 31 microphones was used in this study to determine the BTI noise source. With the Clean-SC approach, clear and quantitative sound radiation results of the leading-edge noise source of swept blade are obtained. Parametric studies of the WLE amplitude and wavelength are conducted to understand the effect of WLE on BTI noise reduction. It is observed that the OASPL reduction is sensitive to both the amplitude and wavelength of the WLE. The WLE with the largest amplitude and smallest wavelength can achieve the most considerable OASPL reduction up to 2dB. It is found in this study that the spectra of BTI noise reduction with Strauhal number is almost the same for same WLE under different airflow velocities.

Keywords: Broadband noise; Wavy leading edge; Sweep blade; Source identification; Microphone array

1. INTRODUCTION

The reduction of the turbulence broadband noise from the trailing-edge (TE) and leading-edge(LE) of wing or the turbomachinery blade is nowadays an important industrial need and probably one of the most challenging issues in aero-acoustics. Especially, the Blade-Turbulence Interaction noise (BTI noise) which from the interaction between the incoming turbulence and blade leading edge is a significant contributor to the noise of turbofan, wind turbines, ventilation systems, high-lift devices, propellers, and so on. It has been found that the BTI noise can be the dominant source when the incoming turbulence intensity is sufficiently high[1], which is often the case at the leading edge (LE) of outlet guide vanes in modern high-bypass-ratio turbofan engines.

The wavy or serrated leading edge (Wavy Leading Edge, WLE) was originally bioinspired by owl serrations leading-edge wings and Humpback whale flippers, has been identified as a lift-enhancing, drag-reducing and noise reducing modification[2-5]. In addition to the aerodynamic aspects, many studies have focused on BTI noise reduction with the WLE in recent years[6-23]. Clair et al.[6] experimentally and numerically investigated the effects of wavy leading-edges on the airfoil-turbulence interaction noise, reporting a noise reduction of 3-4 dB. Lau et al.[7] numerically investigated the effects of wavy leading-edges on the airfoil-gust interaction noise(AGI), finding that the ratio of the wavy leading-edge peak-to-valley amplitude (A) to the longitudinal wavelength of the incident gust (λg) was an important factor in reducing AGI noise. Kim et al.[11] conducted a numerical investigation into the noise reduction mechanisms of wavy leading-edges, obtaining valuable results. Mathews and Peake[12] and Lyu et al.[13] also performed theoretical analyses of noise reduction using wavy leading-edges. Chaitanya et al.[14] conducted a detailed parametric study of the sensitivity of noise reduction effects to the amplitude and wavelength of the leading-edge serrations of flat plates and a NACA-65(12)10 airfoil. The influence of the turbulence integral length scale is also studied. Biedermann et al.[15] proposed a statistical-empirical model to predict the noise generated by wavy leading-edge airfoils. Turner and Kim[16] numerically investigated the aeroacoustic source mechanisms of wavy leading-edges on a flat plate, identifying a system of horseshoe-like secondary

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vortices developing around the wavy leading-edge. Aguilera et al.[17] investigated the interaction of anisotropic turbulence with a wavy leading edge NACA 0012 airfoil by means of computational aeroacoustic simulations (CAA). Reboul et al.[18] performed a CAA prediction of the broadband noise reduction effects of a serrated OGV using synthetic turbulence. A reduction in overall sound power level of 1.9 dB was reported[18]. More recently, a series of experimental and numerical simulation studies on the broadband noise reduction with WLE was carried out by present authors in Northwest Polytechnic University(NPU)[19-22].

Despite the rapid growth in this field, the understanding of the noise reduction mechanisms associated with wavy leading edge is still underdeveloped[23]. For the above wavy leading-edges research work, most of the studies have been focused on 2-dimensional airfoils and flat plates with 2-dimensional flow and most previous studies have used homogeneous isotropic and grid generated turbulence. To the authors' knowledge, real fan noise reduction using wavy leading-edges has only been reported recently by Tong et al.[24] and Reboul et al.[25](in fact, the simplified approximate two-dimensional flow simulation method is still used in these study[24]), and the investigation of leading-edge noise reduction with incoming anisotropic turbulence has only been reported recently by Chen et al.[18-21] and Tong et al[22]. It is well known that the flow around blade of turbomachinery presents a strong three-dimensional flow characteristic. It could be expected that the flow and acoustic mechanism of the wavy leading edge in turbomachinery are more sophisticated than that in the already existing theory with the supposing of 2-dimensional flow around airfoil.

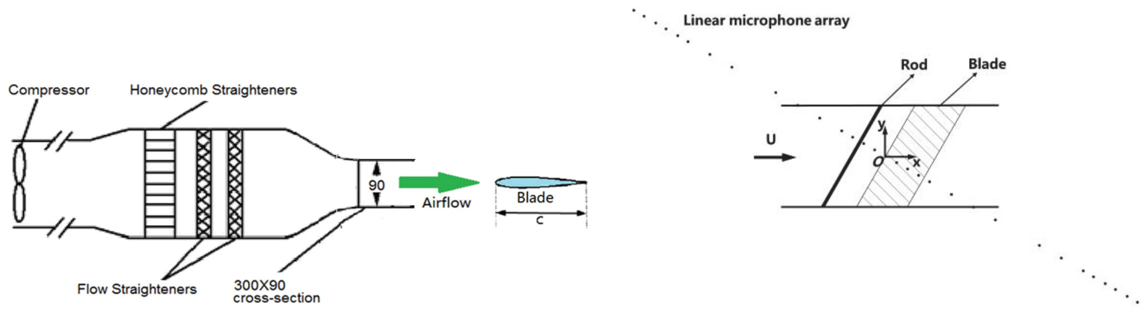
In the current work, a swept blade which model the three-dimensional flow characteristics around blade is used to study the BTI noise reduction mechanism of wave leading-edge configuration.

2. EXPERIMENTAL SET-UP AND BTI NOISE IDENTIFICATION METHOD

2.1 Test facility

The experiment was carried out in the low speed open jet wind tunnel in Northwestern Polytechnical University, and a swept blade with sweep angle of 30 degrees and constructed by NACA0012 airfoil was experimental investigated in this study. Air is supplied by the wind tunnel at Mach numbers ranging up to 0.35, with the Reynolds numbers based on blade chord ranging from 1.0×10^5 to 1.0×10^6. The turbulence intensity at outlet of the wind tunnel is keep below 1%.

A test swept blade with a 150 mm chord and 300 mm span is placed into the core of an open jet of the tunnel exit which is shown in Fig. 1. The swept blade is mounted onto a plexiglass disk, which allows tuning the angle of attack α from -5 to +5 degree as shown in figure 1(b). A circular rod with the diameter of 10mm is placed 100mm in front of the blade leading edge with the same sweep angle as that of swept blade. The anisotropic turbulence in this circular rod wake will interact with the swept blade and generate the leading edge noise(BTI noise).



(a)The test setup (b)The test swept blade and microphone array

Fig. 1. Test set-up and Microphone array

An unequal spacing linear microphone array with 31 microphones (as shown in Fig. 1(b)) was used to identify the sound source around airfoil and to analysis the noise strength and spectra. The array was placed just underneath the test blade about 0.69 m and the center of the array was placed underneath the center of the blade. The direction of the linear array is perpendicular to the leading edge of the swept blade. The total length of the array is 1720 mm. The maximum distance between adjacent microphones in the array is 150 mm and the minimum distance is 35 mm. The all microphones with its diaphragm were mounted on a large, hard reflecting surface so that the sound pressure levels obtained will be augmented over the whole spectrum, up to the frequency at which incident and reflected waves interfere, by a factor of 2 (6 dB).

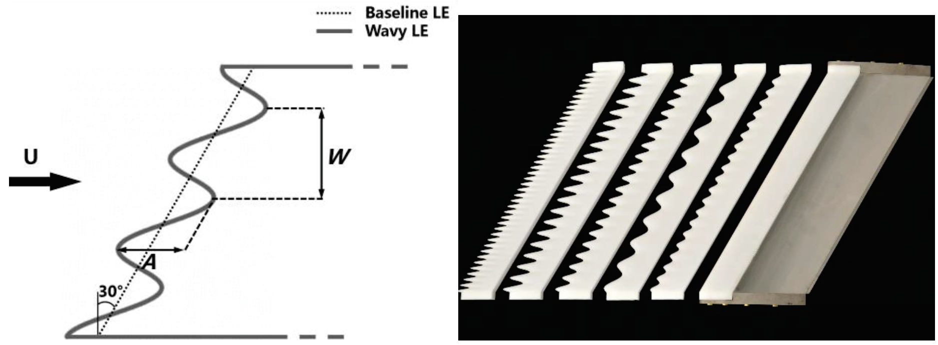
An improved sensitivity beam-forming technology to remove the spatially coherent background noise and reduce the beam width based on the deconvolution array data method, Clean-SC which developed by Sijtsma[28,29]. In order to quantify BTI noise, the sound level of BTI noise source is calculated by superimposing and averaging the sound energy of leading-edge noise in a certain space range.

2.2 Design of the wavy leading edge of swept blade

The swept blade with swept angle of 30 degrees and constructed by NACA0012 airfoil was investigated in this study. The chord of the swept blade is of 150mm and the span is of 300mm.

In order to investigate the effect of wavy leading edges on the BTI noise, the swept blade with modified leading edges, i.e. wavy leading edges, is designed as shown in figure 2. The wavy peak, middle, and valley(trough) locations are also depicted in this figure. The averaged Leading Edge(LE) line of the WLE blade coincides with the LE of the Straight Leading Edge(SLE) blade so that the mean chord length and the wetted area of the WLE blade are maintained constant as that of SLE blade. The WLE blade in the form of sinusoidal profile with amplitude A, wavelength W, and mean chord length c is shown in figure 2. It should be noted that the wave shape in figure 2 is obtained by projecting a sinusoidal line with amplitude A and wavelength W perpendicular to the flow direction to the blade span direction. Therefore, the wavelength W is perpendicular to the direction of the inflow. The symmetrical lines of the sinusoidal profile passing through the crest and valley points of the wave are parallel to the flow direction of the airflow. The chord length of the WLE blade versus spanwise coordinate z is of the form

$$c(z) = \bar{c} + \frac{A}{2} \cdot \cos\left(\frac{2\pi z}{W}\right) \tag{1}$$



(a) (b)

Fig.2 The wavy leading edge for swept blade

Five wavy blade modifications comprising all combinations of the sinusoidal serrations of different amplitude (A/c) of 5%, 10% ,15% and wavelength (W/c) of 5%, 10%, 20% are designed in this study. All wavy blades are labeled by the combinations of the non-dimensional percentage of the amplitude and wavelength. The sweep angle of the swept blade is labeled using S30, that means the sweep angle is 30 degree. The ranges of the non-dimensional wavy amplitude-to-wavelength ratio (A/W) is from 0.5 to 2.0. In order to facilitate the replacement of wave leading edge blades and control the cost of experiment, a demountable blade test piece is adopted in this test. When replacing the experimental blade, only the wavy leading edge was replaced. The wavy leading edge is made of organic resin and is formed by 3D printing as shown in fig 2(b).

3. TEST RESULTS

The BTI noise for the swept blade with and without wavy leading edge were tested with the flow speeds of U=30m/s, 40m/s, 60m/s and 70m/s, and the corresponding Reynolds numbers based on the airfoil chord are respectively of 30,0000 ~ 70,0000.

3.1 The spectra of the BTI noise of the swept blade

The spectra of BTI noise at different airflow velocities is presented in figure 3. It can be clearly seen that there is same obvious tone noise at low frequencies with St=0.153 at four different airflow velocities. According to Berland's theory[31], when the rod is far away from blade(L/d is larger than 3.5), the flow pattern behand circular rod is "wake mode". In this test, the ratio of the distance between rod and the blade leading edge to the rod diameter L/d=10, the flow behand of the rod is "wake mode" flow pattern according to Berland's theory. The tone noise is caused by periodic interaction between the Karman Vortex Street and the leading edge of the blade, and the broadband noise is generated by the interaction between wake turbulence and blade leading edge. As we all know, the dimensionless frequency of Karman Vortex Street is 0.19(Strauhal number) for air flow passing through a cylinder vertically. In this study, the airflow flows passing through the cylinder at an inclination angle of 30 degrees, so the Strauhal number of the Karman Vortex Street will be obviously smaller than that of the cylinder with perpendicular inflow. The Strauhal number of the tone of BTI noise in this study is of 0.153, which is consistent with the results of previous studies on inclined cylinders flow [32].

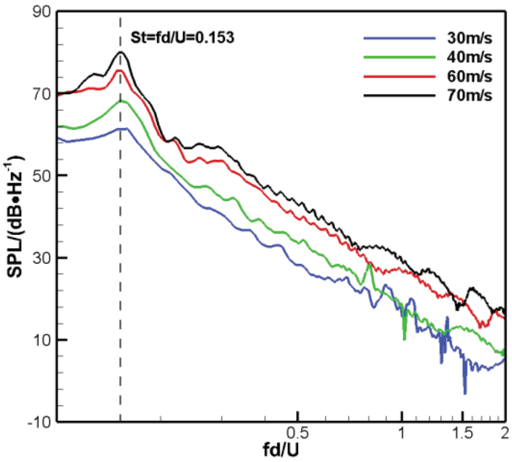


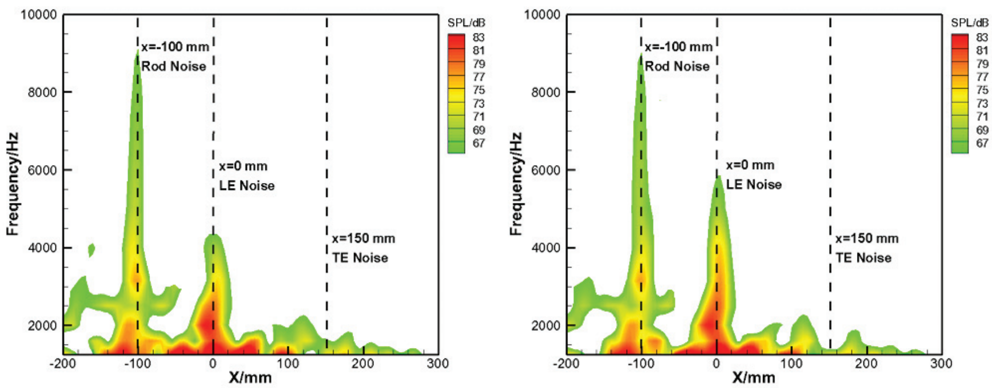
Fig. 3 Spectra of the BTI noise of the swept blade with straight leading edge

3.2 Effect of wavy amplitude on the BTI noise reduction

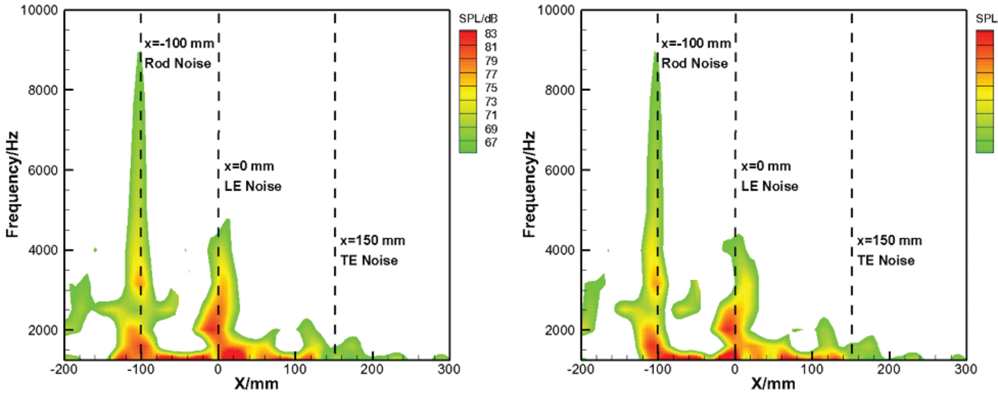
Figure 4 shows the BTI noise source identification results for the straight leading edge blade and the wavy leading edge blades with the same wavelength and with increasing amplitude at the airflow velocity of 70 m/s. It can be seen that the flow noise around a cylinder does not change at the same air velocity. However, BTI noise is changed with the using of wavy leading edge. It could be seen that with the small amplitude wave leading edge, the BTI noise may be increased in the low frequency range relative to the straight leading-edge blade. With the increase of wave amplitude, the noise in low frequency region will be reduced gradually.

In order to quantitatively describe the influence of wavy leading edge on BTI noise, the spectra of BTI noise of swept blade at different airflow velocities with different leading edges were compared. Comparing with the spectral results of straight leading edge blades, the spectrum of BTI noise reduction ΔSPL with the using of wavy leading edge can be obtained,

$$\Delta SPL = SPL_{Baseline} - SPL_{Wavy} \tag{5}$$



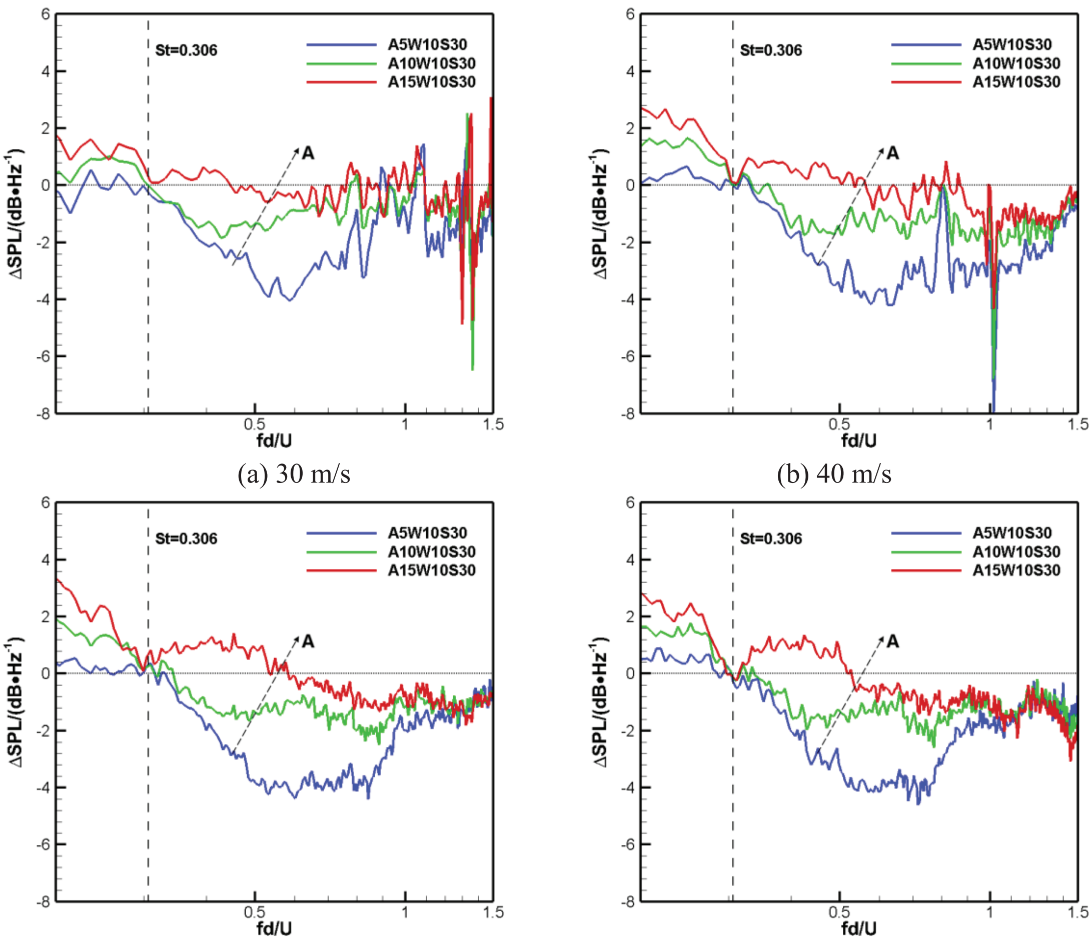
(a) BaselineS30 (b) A5W10S30



(c) A10W10S30 (d) A15W10S30

Figure 4. The identification of rod-blade interaction noise sources (at 70m/s of inflow speed)

Figure 5 shows the experimental results of BTI noise reduction at different flow velocities and with different wave amplitude at same wavelength of 0.1c. It can be clearly seen from this figure that the noise reduction of blades with different wave amplitudes tends to decrease with the increase of frequency at various airflow velocities. When the frequency is greater than a certain value, the noise will increase.



(a) 30 m/s (b) 40 m/s

(c) 60 m/s (d) 70 m/s

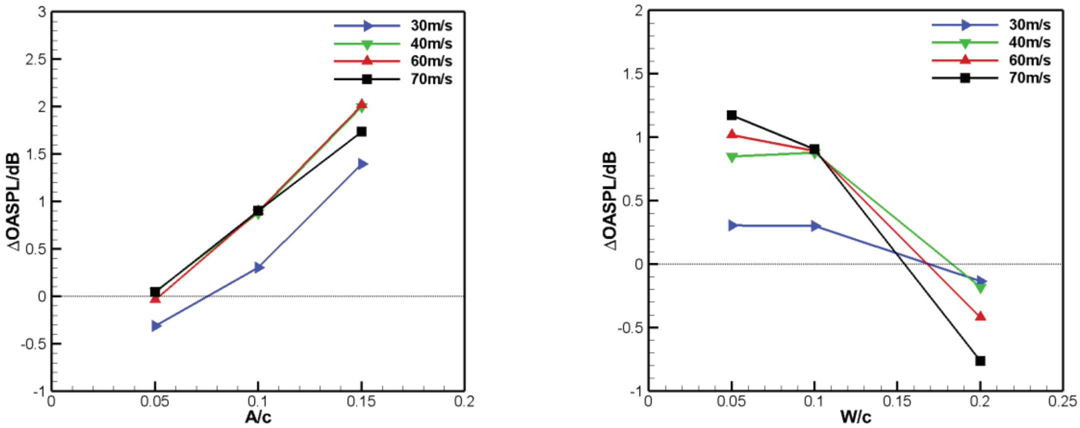
Fig. 5 Spectra of the BTI noise reduction with wavy leading edge at same wavelength

When the airflow velocity is 30 m/s, in the frequency range which the Strauhal number is less than 0.306, the wavy leading edge with the smallest amplitude does not reduce but increase the low-frequency noise. When the airflow velocity is greater than 30 m/s, the wavy leading edge with small amplitude can achieve minimal noise reduction in the low frequency range. Noise reduction increases with the increase of wave amplitude. In the frequency range of Strauhal number less than 0.306, all wavy leading edge can achieve noise reduction for the inflow speed larger than 30m/s. In the frequency range where the Strauhal number is greater than 0.306, the BTI noise will increase using the wavy leading edge with the amplitude smaller than 0.15c.

It is noteworthy that when the Strauhal number is 2 times the Karman vortex street frequency (St=0.306), the BTI noise reduction using wavy leading edge configurations with different wave amplitudes at different airflow velocities is all close to zero. This shows that the noise reduction in the low frequency range is independent of the wave amplitude, but only related to the wavelength.

3.3 Effect of wavelength on the BTI noise reduction

In Figure 6(b) shows the OASPL reduction of BTI noise using WLE at different flow velocities and at same wave amplitude of 0.1c but with different wavelength. The OASPL in fig.6(b) is computed from St=0.2 to St=1.5. As can be seen from the figure, when the wavelength is large, W/c=0.2, the WLE configuration can't effectively reduce the OASPL of BTI noise in the experimental range of airflow velocity, and with the WLE at W/c=0.2, the BTI noise will increase with the using WLE configuration. This shows that noise reduction can't be achieved using WLE configuration with the larger wavelength. At the same airflow velocity, the smaller the wavelength, the larger the OASPL reduction of BTI noise. It is worth noting that with the same wavelength, the higher the airflow velocity, the greater the noise reduction.



(a) with same wavelength (b) with same wave amplitude

Fig. 6 The reduction of the OASPL of the BTI noise with wavy leading edge

3.4 Effect of inflow speed on the BTI noise reduction

In fig. 7 shows the OASPL reduction of BTI noise with different amplitudes and wavelengths at different airflow velocity. It can be seen from fig. 7 that in the experimental range of airflow velocity, when the airflow velocity is of 30m/s, the OASPL reduction is small with WLE configuration. When the airflow velocity is of 40m/s, the OASPL reduction is obviously increased. However, with the further increasing of airflow velocity, the OASPL reduction of BTI noise does not change much. It could be also obviously seen from fig. 15 that WLE configuration of swept blade will not reduce the BTI noise if the ratio of amplitude to wavelength of the wavy leading edge is too small(0.5).

4. CONCLUSIONS

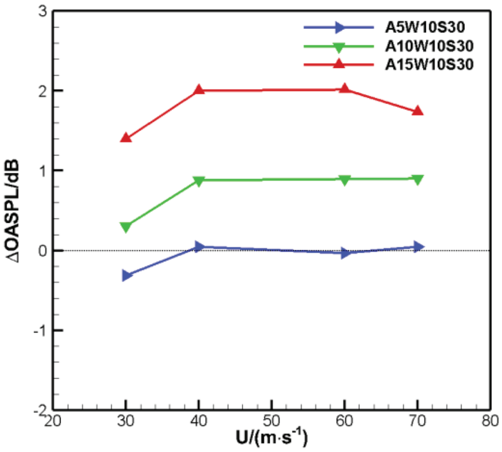
(1) Wavy leading edge will reduce the BTI noise of swept blade in low-frequency range, however, WLE will increase BTI noise in high-frequency range. Within the range of experimental parameters, not all wave leading edges can reduce BTI noise of the swept blades. If the wave amplitude is too small or the wave length is too large, the OASPL of the BTI noise will be increased.

(2)The amplitude and wavelength of wavy leading edge significantly affect the noise reduction spectrum. The wavelength of WLE will also affect the frequency range of noise reduction. The larger the wave amplitude of WLE, the larger the noise reduction in the low frequency range. The smaller the wavelength of WLE, the larger the frequency range of BTI noise reduction.

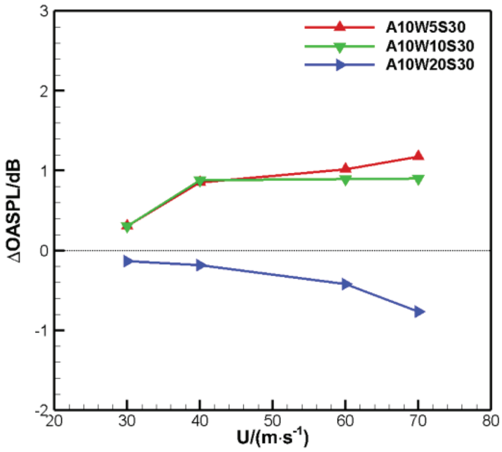
(3) The larger of the wave amplitude of wavy leading edge, the larger of the OASPL reduction of BTI noise. The smaller of the wavelength of WLE, the larger of the OASPL reduction of BTI noise.

However, in the case of fixed wave amplitude, there will be a minimum wavelength limit, when the wavelength is less than this value, further reducing the wavelength will have no effect on noise reduction.

(4) The spectra of BTI noise reduction with Strauhal number is almost the same for same WLE under different airflow velocities. For the WLE with the same wavelength of 0.1c, the dimensionless Strauhal number at that the BTI noise reduction is zero will keep as a constant of 0.306 under different airflow velocity. However, for the WLE with the same wave amplitude, the dimensionless Strauhal number at that the BTI noise reduction is zero will be changed with the changing of the wave length. The smaller the wavelength is, the larger the Strauhal number with zero noise reduction is, and it gradually increases from 0.216 to 0.508 when wave length increase from 5mm to 20mm.



(a) WLE with same wavelength



(b) WLE with same wave amplitude

Fig. 7 The reduction of the OASPL of the BTI noise with wavy leading edge at different inflow speed

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