NOISE SOURCE ANALYSIS AND CONTROL FOR TWO AXIAL-FLOW COOLING FANS IN SERIES

Chen WANG[1], Weihao ZHANG[1, 2], Lixi HUANG[1]

[1] *Lab of Aerodynamics and Acoustics,*
HKU Zhejiang Institute of Research and Innovation
and Department of Mechanical Engineering,
The University of Hong Kong, Hong Kong

[2] *School of Energy and Power Engineering,*
Beihang University, Beijing, China

SUMMARY

The noise signature of two identical small axial-flow cooling fans in series was analyzed and a technique of time-base stretching synchronous averaging was used to perform the noise source distinction. Acoustic directivity measurements were conducted for two configurations. First of all, the inlet flow to the upstream fan is a free-field. The effect of a flow straightener placed between the two fans was studied as well. It just changes the proportion of each noise source in the total noise. Second, the inlet flow is distorted by a flat plate covering one half of the inlet flow passage. The same flow straightener is mounted at the inlet of the upstream fan to reduce the negative effect of the inlet flow distortion. The total SPL is reduced by 2.5 dB in average.

INTRODUCTION

Fan noise is a serious issue in electronic cooling applications. The pioneering work on cooling fan noise was finished by Huang [1] in 2003. His study first reviewed the research on the general fan aeroacoustics and those considerable efforts made for noise abatement of small axial-flow fans systematically. It is well-known that the details of the sound field of a point force in arbitrary motion are available in Lowson [2, 3] in 1965 and 1970. In consideration of a likely trend towards swept and leaned blades, however, the contribution of the unsteady radial force component was firstly complemented by Huang [1] except for the axial thrust and circumferential drag force components. Wang and Huang et al. [4] later summarized the important mechanism of fan noise generation and categorized the sound radiated by a computer cooling fan into tonal noise which are phase locked with the rotation and broadband random noise. An active noise control method was used to control the tonal noise radiated by the thrust force component, which was the most annoying part of fan noise and was more likely to be controlled. Following the previous study, Wang and Huang [5] turned to more complicated cases i.e. active control of drag noise which was the more common and popular condition of computer cooling fans and required more complicated experiment equipment than the thrust noise control. Huang and Ma et al. [6] proceeded to address the broadband random noise, especially in the low frequency range. Since the traditional duct lining became ineffective for such a problem, they proposed a reactive method to attenuate the noise and subsequent experiment successfully verified the effectiveness of the method. In contrast to the studies above which all aimed at improving practical application by experiments to some extent, Lu and Huang et al. [7] focused on the fundamental aerodynamic mechanism of rotor-strut interaction for a computer cooling fan by the numerical simulation method and several interesting and new findings were pointed out although they were obtained from the specific fan used in the study and their generality remained to be proved.

Usually one single fan is enough in applications such as computer cooling fans and building ventilation fans. However, when pressure drop is high, two axial-flow fans in series are often used and the noise created by the two fans is complex. For one single typical computer cooling fan, the dominant noise source is the aerodynamic interaction between the impeller blades and the downstream struts, which support the motor assembly and carry the electricity wires. Besides, two other undesirable features, which may become extra noise sources, are easily noted. One is the incomplete bellmouth cut by the square outer casing. As a result, the four sharp edges disturb the inlet flow field acting like four independent noise sources. The other is the extra size of one of the struts required for carrying wires. Wang and Huang [8] made great progress through structure design correction of cooling fans and the results showed that around 10 dB sound power reduction can be achieved by correcting both the two design faults. In this study, two identical small axial-flow cooling fans in series (a two-stage fan) were investigated experimentally. The fan is 120 mm in casing diameter and it has 7 rotor blades and 11 stators behind the rotor to change the flow direction and support the motor assembly. Noise radiated by a two-stage fan is more complicated and the main noise sources are found to be 4 parts: (1) inlet flow distortion caused by incomplete bellmouth cut by the square outer casing; (2) and (3) interactions of rotor blades with downstream stators for both stages; (4) interaction between the stators of the first stage and the rotor blades of the second. A technique of time-base stretching synchronous averaging [9, 10] was used to separate the rotary (or discrete) and random (or broadband) noise for both stages (source distinction). In the following, this technique including the experimental setup is described first, followed by an explanation about how the source distinction works. Then the experimental study analyzes the noise signature and the source distinction guides the efforts to control the overall noise radiation.

EXPERIMENTAL METHODOLOGY

Experimental Set-up

Figure 1 shows the schematic diagram for the acoustic directivity measurement. The whole measurement is conducted in an anechoic chamber. The sample fan is installed vertically on a podium. A tachometer (ONO SOKKI Digital Tachometer HT-5500) with pulse output is installed at the inlet of the fan. The signal from the tachometer is used as trigger to correct the variation of instantaneous rotational speed in every cycle or revolution and exclude the sub-BPF noise from the background. Sound is measured by a ½ inch B&K microphone (Type 4955), powered by B&K Nexus conditioning amplifier (type 2690). The sound is measured at an interval of 30 degrees by manually rotating the microphone along a circle of 0.8 m in diameter on the central horizontal plane with the fan at the center. The monitoring point at the outlet (α=180°) is left out since its noise data is inevitably contaminated more or less by the oncoming wind while 0° represents the fan inlet. The signals from the tachometer and microphone are sampled by a 16-bit NI A/D card (NI USB-6251), and then processed in a PC equipped with MATLAB.

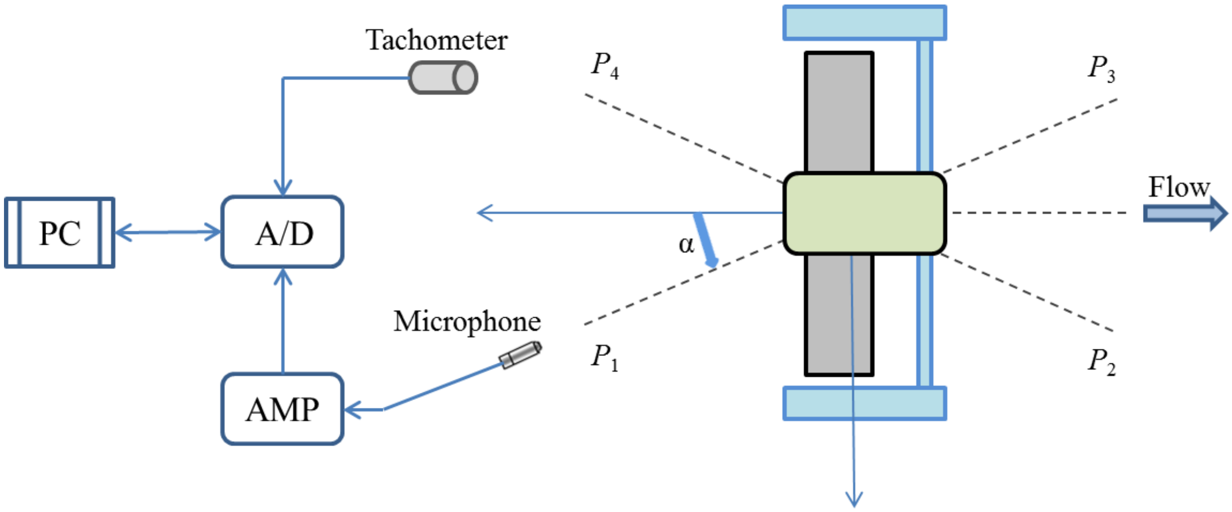

Figure 1: Experimental setup for acoustic directivity measurement

Signal Measurement and Processing

The fan rotating at the speed of 4200 rpm, or 70 revolutions per second (rps) is used. The signals are sampled at a rate of f_s=21 kHz. The fan has 7 blades (B=7) and 11 stators (S=11). Thus, N= f_s/rps=300 data points are obtained during one complete rotational cycle. The measurement time of duration for all the positions measured are t=10 s, which gives rps×t=700 cycles for averaging.

Typical traces of the two channels are shown in Fig. 2. The upper part is the tachometer signal, while the original raw pressure signal of sound in time domain is shown in the second part marked with red curves. The period of each rotational cycle is found by the adjacent tachometer pulses. The signals between the two rising edges of the pulses (trigger signal) are treated as one complete rotational cycle. The standard deviation of instantaneous speed (rpm) is about 5–10, and the difference between two consecutive cycles is about 2 data points. During the post-processing of data in the code, the raw signal is digitally resampled to 300 points in every cycle using time-base stretching to correct the effect of rotational speed variation, which gives the time-base stretched pressure signal in time domain shown in Fig. 2 with green curves. Then the resampled cycles are

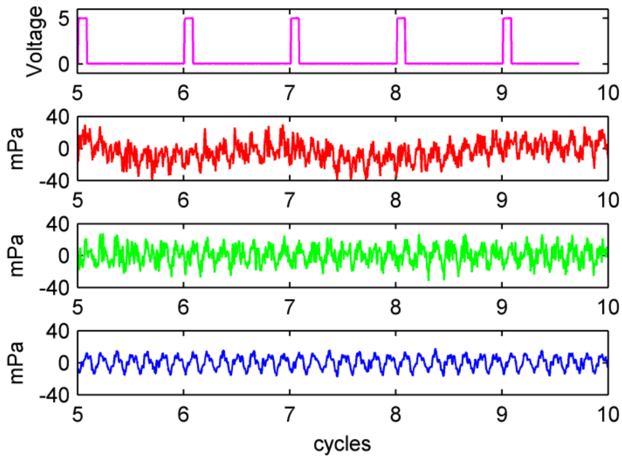

Figure 2. The two channels of raw signals, together with the time-base stretched and synchronous averaged pressure signals

overlapped for averaging which gives a time-base stretched and synchronous averaged pressure signal. The result is the rotary sound shown in the lower part, from which seven more periodic waveforms can be easily identified in one rotational cycle. That is just the number of rotor blades. The difference between the raw noise power and the rotary sound power is defined as the random noise power. In fact, the method of synchronous averaging is not new, e.g., Washburn and Lauchle in 1988 [11], but the use of the time-base stretching appears to be less common, to the best of the author's knowledge. If the raw signals are not processed using time-base stretching, random noise energy is found to be increased while the rotary noise is decreased due to the variation of rotational speed in every cycle. In other words, the energy of rotary noise "leaks" into that of random noise.

The spectrum of the raw signal is shown in Fig. 3 as a green bar chart, while that of the rotary sound is plotted as a black one. The frequency resolution shown in the abscissa is *f*/rps, and the frequency index of B=7 represents the BPF. Since signals below 420 Hz or 6 rps, are contaminated by the microphone self-noise and are filtered out, the attention is focused on the noise at BPF and above. Theoretically, the only harmonics that radiate sound are those for which $n = mB$ for a B evenly spaced rotor blades, where m is an integer. The total sound is simply B times the sound made by each individual blade while for other harmonics the sound form each blade cancel with each other due to the inter-blades phase difference. However, in reality unevenly spaced rotor blades is the much more common case due to the inevitable machining error and other factors. Thus, sound can appear at all rps harmonics instead of just BPFs.

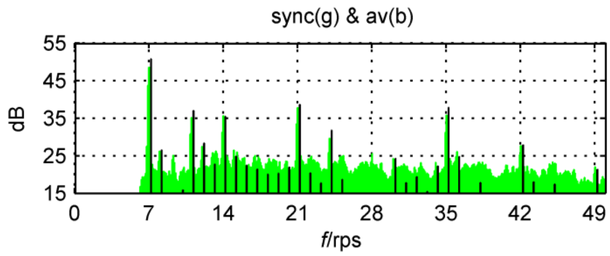

Figure 3. Comparison of the spectra for the raw signal with averaged signal

SOURCE DISTINCTION

Source Distinction for Two Fans in Series in Free Field

From the above, the technique of synchronous averaging can decompose the noise contributions made by the discrete and broadband components when it refers to a single fan. For the studied case of two fans in series, the discrete noise made by the one whose rotational signal the tachometer samples is used as the trigger signal in the code can be separated from the total noise while the discrete noise made by the other fan is counted into the broadband part. Therefore, to study the discrete frequency noise, different rotational speeds (a 35 rpm difference is selected and the downstream fan has higher rotational speed) are used for the two fans to distinguish the noise sources. In fact, the discrete noise made by the two fans can still be distinguished by the code even if we use the same one channel control of their motors, which was confirmed in our research. First of all, the rotary components of upstream and downstream fan can be obtained successively by two measurements of the two-stage fan, each with the rotational signal of the upstream and downstream fan as the trigger signal respectively. For the broadband noise, the method of subtraction is used to estimate the contribution of each fan. In this method, the noises made by one and two fans are measured and the difference is considered to be the noise made by the downstream fan.

Figure 4 shows the measurement results of acoustic directivity for two fans in series with a 35 rpm difference. In the legend, "Rotary" and "Random" mean the rotary and random components of the total noise. "1" and "2" represent the upstream and downstream fan respectively. From the comparison of Fig. 4, the rotary noise source of the downstream fan is larger than that of the upstream fan, the difference being 2.7 dB in average in the whole measurement positions. It does not result from the 35 rpm difference which can be validated by the fact that it gives the same conclusion when they have the same rotational speed. For the broadband component, the downstream fan contributes 3.8 dB more than the upstream one in average. This is due to the source distinction method used for broadband noise to a large extent. “Random 1” is just the broadband noise of one single fan while “Random 2” contains not only the broadband noise made solely by the downstream fan, also the interaction broadband components between the two fans in series. In addition, the ability of the code to tell the discrete noise of the upstream fan from that of the downstream fan is confirmed when one channel is used to control their motors and thus they have very close rotational speed. Furthermore, the rotary noise energy contains both BPF content (BPF and its harmonics) and rps content (rps and its harmonics). It indicates that the BPF content accounts for more than 90% of the rotary energy for both fans. Figure 5 indicates that the sound pressure level (SPL) increases by 6.2 dB in average, when lining up two identical fans compared with one single fan.

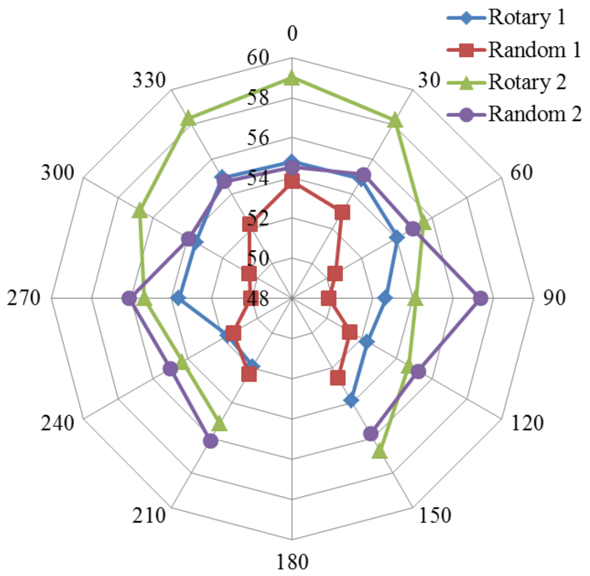

Figure 4. Measurement results of acoustic directivity for two fans in series in free field

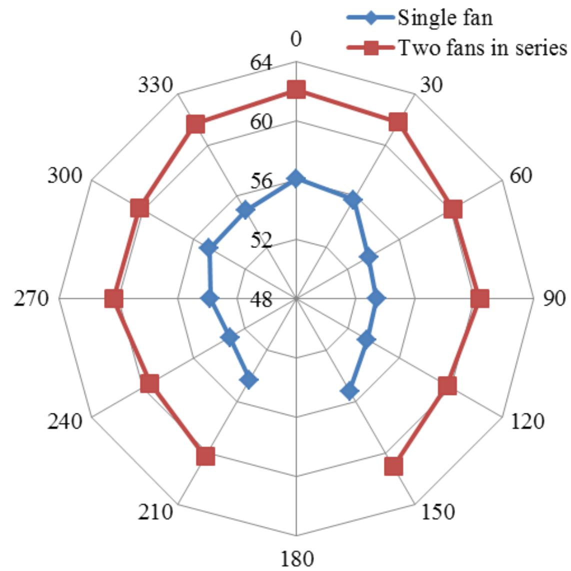

Figure 5. SPL comparison of two fans in series with one single fan

Source Distinction for Two Fans in Series with a Flow Straightener Between Them

This is further coupled with the measurement of noise when a flow straightener is used for the inlet of the downstream fan. The flow straightener consists of many small hexagons of 2 mm in side length, 0.1 mm in thickness and 7 mm in depth. Figure 6 shows the measurement results of acoustic directivity for two fans in series with a 35 rpm difference and a flow straightener between the two fans. The comparison of Fig. 6 with Fig. 4 indicates that the rotary noise of the downstream fan is suppressed by 1.2 dB in average while its random noise increases by the same figure. In addition, the rotary noise of the upstream fan also increases by 1.9 dB. Within the Rotary 1 energy, both BPF and rps contents increase, but the proportion of rps content increases. However, the contents of Rotary 2 energy show a different trend. The BPF content decreases while both the rps content and its proportion in Rotary 2 energy increase a little. All these changes of the proportion of each noise source in the total noise should be attributed to the flow straightener. It is well known that due to losses in the boundary layer, a spatially and temporarily non-uniform flow velocity is generated by the upstream rotor blades. This flow containing velocity defect or viscous wake impinging on the leading edge of the downstream rotor blades will generates a considerable unsteady lift and thus discrete noise. However, with a flow straightener at the inlet of the downstream fan which just plays the same role of a honeycomb device in a wind tunnel, the upstream non-uniform flow can be homogenized greatly before impinging on the downstream rotor. This function reduces the discrete noise component, in the meanwhile increases the turbulence intensity of the flow and thus increases the broadband noise. The total SPLs between the case with a flow straightener and the one without it are compared as well shown in Fig. 7. It can be seen that the flow straightener does not change the SPL a lot, only a 0.3 dB increase in average. Instead, it just changes the proportion of each noise source in the total noise. However, it should be noted that those are the results in free space. The influence of the flow straightener may differ when the fan is installed in a duct fitted with a pressure control valve, such that the noise measured simulates the real working condition with a desired system loading.

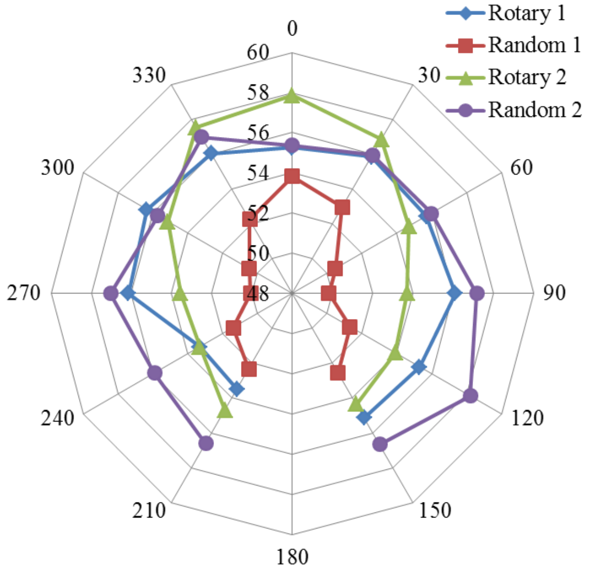

Figure 6. Measurement results of acoustic directivity for two fans in series with a flow straightener between the two fans

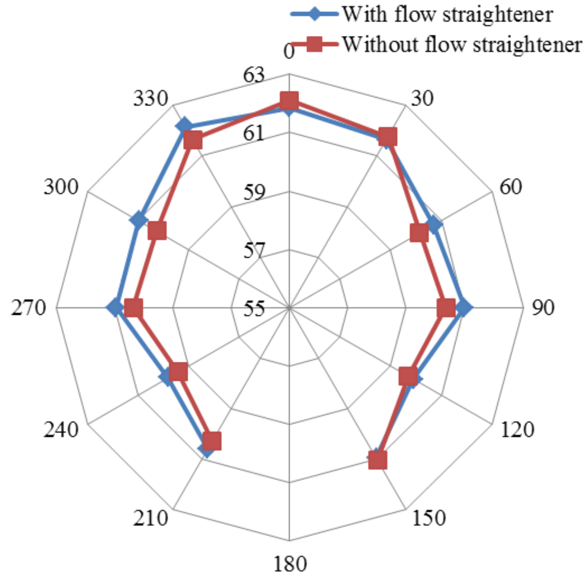

Figure 7. SPL comparison between the two cases with and without a flow straightener between the two fans

INLET FLOW DISTORTION AND ITS NOISE CONTROL

Source Distinction for Two Fans in Series with Distorted Inlet Flow by a Flat Plate

In previous study, the inlet flow to the upstream fan is a free-field while in practical applications the inlet flow is more or less distorted by typical obstacles. Therefore, the case of a simplified flat plate covering part of the inlet flow passage is studied and analyzed in this section. With the knowledge derived from the diagnostic studies of the obtained sound signals, one possible noise control measure is taken and evaluated.

The flat plate is 60 mm in height and 120 mm in width. Thus it covers one half of the inlet flow passage when it is vertically mounted in front of the fan. This flat plate is connected to another one which is placed horizontally parallel to the bottom side of the square outer casing of the fan. In consideration of the symmetry of the fan structure and symmetrical radiated noise directivity indicated in our previous study, measuring only half, divided by the axis of symmetry, will suffice. In addition, the monitoring point at the outlet was still left out since its noise data was inevitably contaminated more or less by the oncoming wind. That means that six positions (α=0°, 30°, 60°, 90°, 120° and 150°) were measured here. Five different axial distances (15, 20, 30, 40, 50 mm) between the plate and fan inlet are conducted and compared with the case of free-field inlet flow for both total SPL and each noise source component (see Fig. 8). From this section on, the random noise is studied as a whole instead of separating it into two random components made by the upstream and downstream fan as before. First, the total SPL increases when the plate is moved closer towards the fan inlet as expected. Random noise component indicates the same trend as total SPL since more intense turbulence is generated by the inlet flow distortion caused by the flat plate. The rotary noise component radiated by the upstream fan does not vary very much at 0°, 30° and 60° positions, but increases at other positions with decreased axial distance between the plate and fan inlet. It can be understood as that this plate act, to some extent, like an independent discrete noise source compared with the uniform inflow for the free-field inlet flow. By contrast, the rotary noise component radiated by the downstream fan nearly keeps in the same level at all directions, which shows that the plate barely has an effect on the downstream fan.

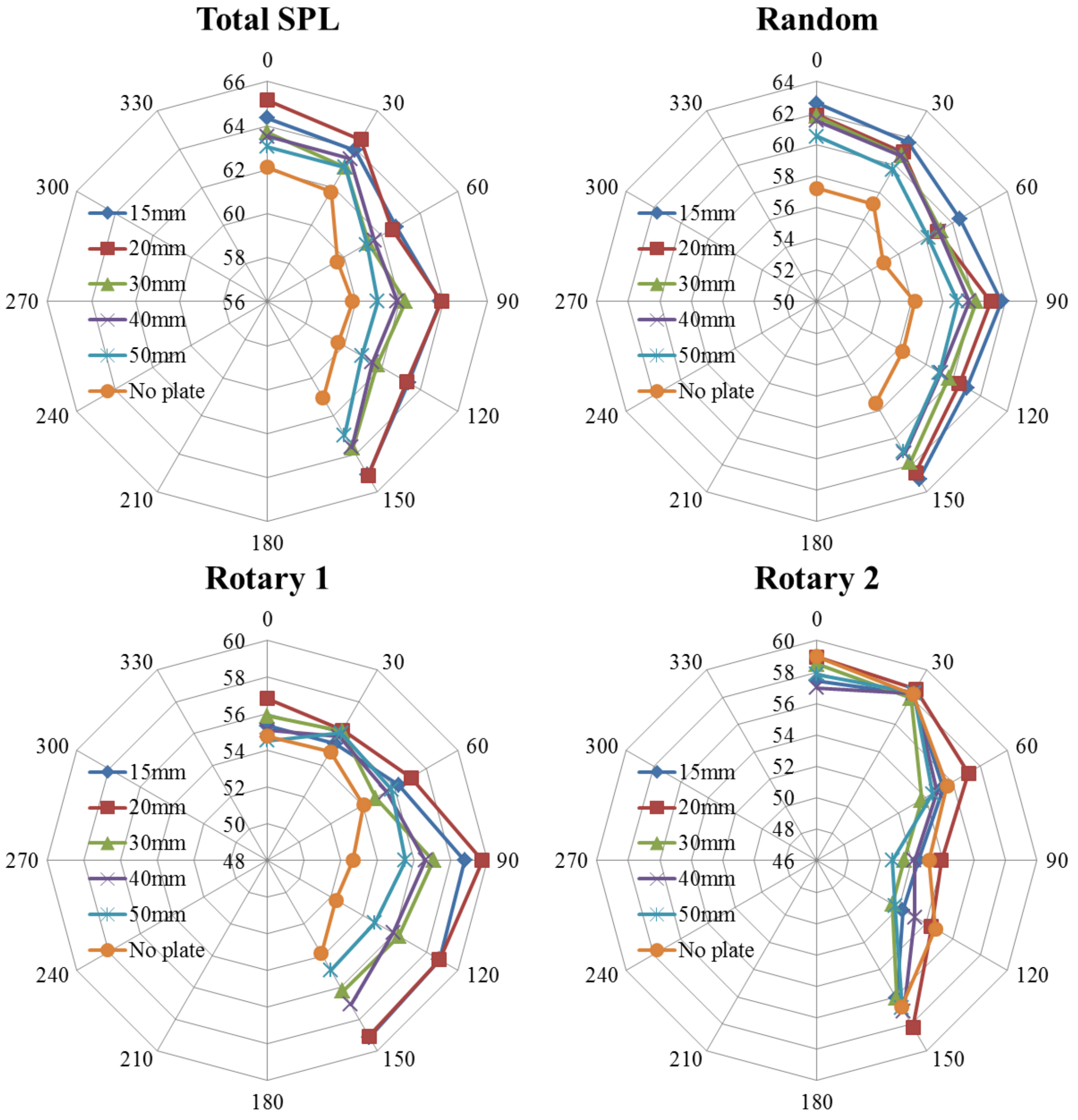

Figure 8. Noise directivity comparison between the cases of distorted and free-field inlet flow

Noise Control of Inlet Flow Distortion by a Flow Straightener at the Inlet

The same flow straightener is used in front of the upstream fan here, instead of between the two fans, to reduce the negative effect of the inlet flow distortion caused by the flat plate. Here, the axial distance between the plate and fan inlet is fixed at 20 mm. Figure 9 shows the noise directivity measurement results for both the cases with and without a flow straightener in front of the upstream fan, including the case of free-field inlet flow as well. First of all, the flow straightener almost eliminates the effect of the flat plate on the rotary noise component radiated by the upstream fan while hardly affect the rotary noise component radiated by the downstream fan. The BPF content within Rotary 1 shows the same trend with Rotary 1, largely because it makes up over 90% energy of Rotary 1. However, the magnitude of the rps content barely changes while its proportion in Rotary 1 energy increases. For the rotary noise of the downstream fan, that is Rotary 2, the BPF content decreases while the rps content increases both for their magnitudes and proportions, since the total Rotary 2 noise hardly varies after the flow straightener is adopted. In addition, the random noise is only reduced by 1.8 dB, with another 2.7 dB larger than that of the case of free-field inlet flow. On one hand, the flow straightener can reduce the inlet flow distortion by homogenizing the nonuniform incoming flows. However, it increases the turbulence intensity of the flow in the meanwhile and thus increases the broadband noise. In total, the total SPL is reduced by 2.5 dB in average at the six positions studied, with only 0.7 dB larger than the case of free-field inlet flow.

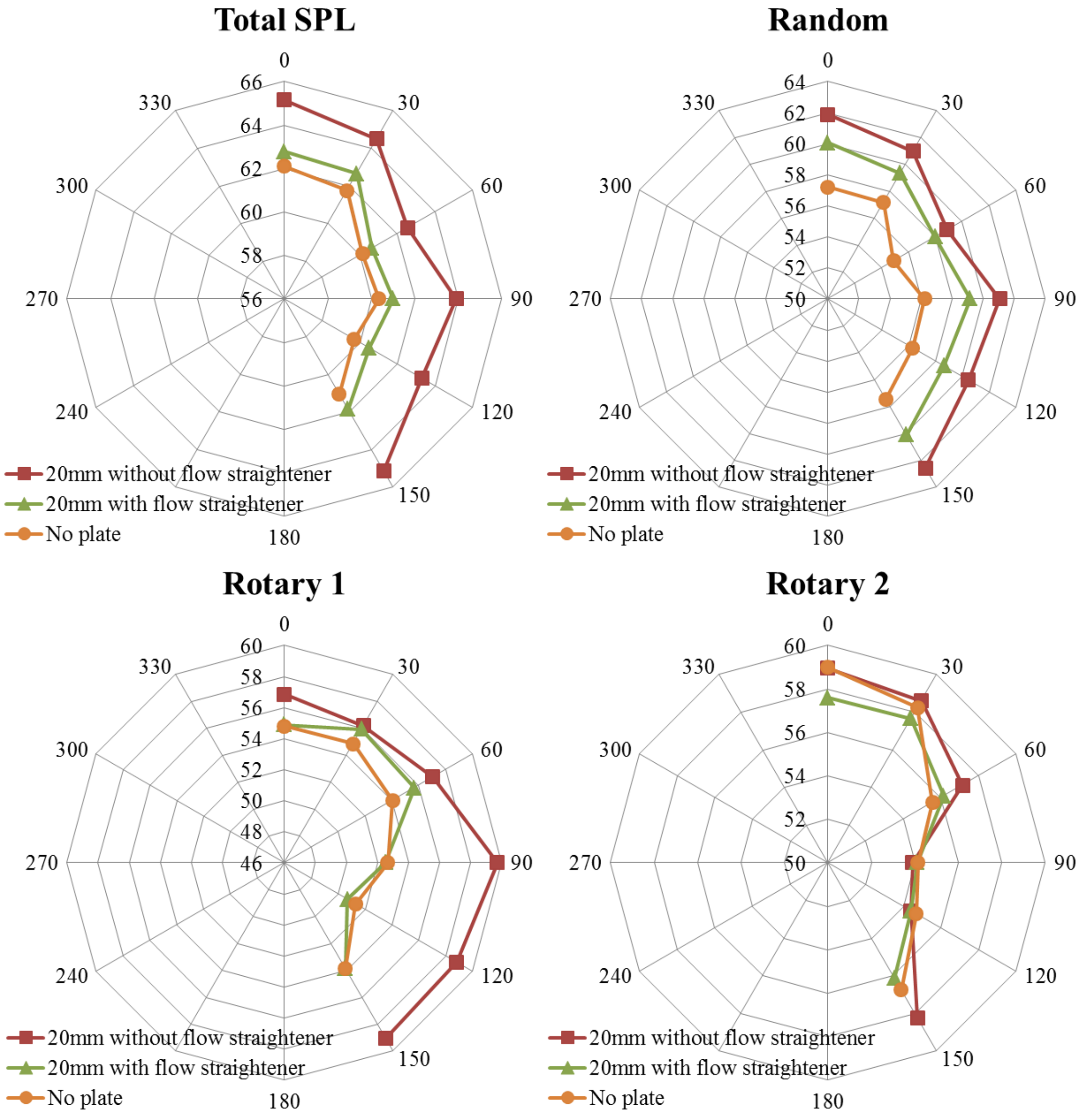

Figure 9. Noise directivity comparison between the cases with and without a flow straightener in front of the upstream fan

CONCLUSIONS

The noise signature of two identical small axial-flow cooling fans in series was analyzed and a technique of time-base stretching synchronous averaging was used to separate the rotary and random noise for both stages. Acoustic directivity measurement and noise source distinction were conducted for two configurations. In the first, the inlet flow to the upstream fan is a free-field. The effect of a flow straightener was studied as well when it was placed between the two fans. In the second, the inlet flow is distorted by a flat plate covering one half of the inlet flow passage. The same flow straightener was mounted at the inlet of the upstream fan in an attempt to reduce the negative effect of the inlet flow distortion caused by the flat plate. The following conclusions can be drawn from the studies.

(i) For free-field inlet flow, the rotary noise source of the downstream fan is larger than that of the upstream fan, the difference being 2.7 dB in average in the whole measurement positions. For the broadband component, the downstream fan contributes 3.8 dB more than the upstream one in average.

(ii) When a flow straightener is used between the two fans, the total SPL does not change a lot, only a 0.3 dB increase in average. Instead, it just changes the proportion of each noise source in the total noise. The rotary noise of the downstream fan is suppressed by 1.2 dB in average while its random noise increases by the same figure.

(iii) For the case of inlet flow distortion by a flat plate, the total SPL and the random noise component both increase when the plate is moved closer towards the fan inlet. The rotary noise component radiated by the upstream fan does not vary very much at 0°, 30° and 60° positions, but increases at other positions with decreased axial distance between the plate and fan inlet. By contrast, the rotary noise component radiated by the downstream fan nearly keeps in the same level at all directions.

(iv) When the same flow straightener is mounted at the inlet of the upstream fan to reduce the negative effect of the inlet flow distortion caused by the flat plate, the total SPL is reduced by 2.5 dB in average at the six positions studied, with only 0.7 dB larger than the case of free-field inlet flow. The flow straightener almost eliminates the effect of the flat plate on the rotary noise component radiated by the upstream fan while hardly affects the rotary noise component radiated by the downstream fan. In addition, the random noise is only reduced by 1.8 dB, with another 2.7 dB larger than that of the case of free-field inlet flow.

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