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Development of low-noise centrifugal fans in a refrigerator

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ABSTRACT

In this paper, low-noise centrifugal fans are developed by applying new design concepts which can reduce the airfoil-self noise by inducing phase difference of potential sources on trailing edge lines of fan blades in the span-wise direction. These design concepts are realized by modifying existing linear trailing edge lines of fan blades into the inclined S-shaped ones. First, to analyze the detailed mechanisms of noise reduction of newly developed inclined S-shaped fans, numerical analysis is made by using hybrid computational aeroacoustic techniques where the computational fluid dynamics (CFD), the acoustic analogy, and the boundary element method (BEM) are sequentially used. The noise reduction of the new fans is confirmed by comparing the predicted BPF noise components of the new fans with those of the existing fan. In addition, it is found that the turbulent kinetic energy of the fluid, predicted for the inclined S-shaped fans, is less than that for the existing fan. This implies that the main mechanism for the noise reduction of newly developed fans is due to the decreased turbulent kinetic energy, which can be considered as a qualitative index for the source magnitude of broadband self-noise. Finaly, the validity of low-design concepts is confirmed by the experiments carried out with four proto type fans. These results show that noise reductions of approximately 2 to 3.5 dB are achieved for the new fans in comparison with the original fan. These reductions are retained over the range of rotation speed of fans from 1800 rpm to 2400 rpm.

INTRODUCTION

With increasing desire for life in pleasant environment, home appliance noise related to it is realized as one of important factors represent its performance. Among various home appliances, coustomers are most sensitive to noise of refrigerators since they generally operate for all day long. Main noise sources of refrigerators are known to be compressors and fans. Fans in refrigerators are used for several purposes: to circulate a cold air around evaporator, to make a peice of ice in an external ice dispenser, and to lower compressor's temperature. In the case of large-sized refrigerators, fans need to rotate more fastly to control higher volume flow rate. This high rotational speed makes fan flow noise problem to be more serious. Therefore, developing low noise fan is essential for the reduction of overall noise of refrigerators, which poises its manufacter for market leadership in the highly competitive hosuehold refrigerator market.

Neise [1-3] extensively reviewed noise reduction methods for centrifugal fans, published until that time, and summarized its effects. It is shown in these works that interaction between flow emitted from blades and the volute tongue region in a duct is main noise sources of BPF(Blade Passing Frequency) noise, and that the BPF noise can be reduced through expansion of a cut-off region. Recently, Lee et al. [4] presented a hybrid method for the efficient prediction method of flow induced noise of centrifugal fans in household refrigerators. With this hybrid method, internal BPF noise of a centrifugal fan in a refrigerator was successfully predicted and subsequent study on the noise reduction measure confirmed BPF noise reduction by extending the dimensionless distance of cut-off region. Although there have been a lot of papers on the centrifugal fan noise for the past several decades, it is difficult to find further innovative measures for the reduction of centrifugal fan noise.

It is well known that flow noise of rotating machines such as fans consists of BPF noise and broadband noise. Therefore, for extra reduction of centrigual fans, these broadband noise components must be tackled. The broadband noise of fans is classified into two types: inflow noise and self noise. The broadband inflow noise is generated by interaction between incident turbulence and rotating fan blades while the broadband self noise is produced by interaction between turbulent component in boundary layer on fan blades and its trailing edge. However, it is difficult to control the broadband inflow noise by designing the targeted fan only because inflow turbulence depends on the surrounding environment of the installed locations of the fan. In this work, therefore, developing low noise centrifugal fans is based on a novel concept of reducing the broadband self noise, which exists even in the unrealistic case of laminar inflow without any incident turbulence. Based on understanding of generation mechanism of broadband self noise, low noise centrifugal fans are proposed, which are realized by inducing phase difference of the potential sources located on the trailing edge lines in the spanwise direction. This innovative concept for low-noise designs of centrifugal fans is analysed by using the computational aeroacoustic methods based on the hybrid method [4], followed by the experiments where the proto-type fans are manufactured and its flow noise reduction are confirmed.

ANALYSIS OF A TARGETED FAN NOISE

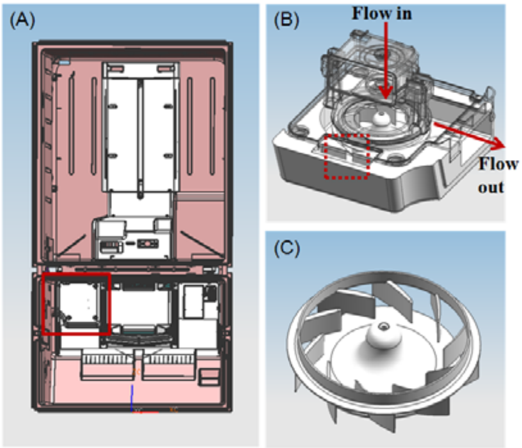


Figure 1. CAD data of the targeted refrigerator: (A) installation position of the targeted fan, (B) the targeted fan system, and (C) the targeted centrifugal fan

Figure 1 presents the CAD data of the inner structure of a household refrigerator with a targeted fan and its outer case with a DC motor. The targeted centrifugal fan has ten backward-curved blades with linear trailing edge lines. The designed rotating speed of the fan is 2,100 RPM. The fan case has a draining hole which is used to remove droplets generated during specific cycles of fan operation. If these droplets are not removed, they become ice in the fan case, resulting in adverse effects on fan performance. Previous work [4] showed that the draining hole induced flow patterns similar to those around the volute tongue; therefore, the hole contributed significantly to the overall noise of the fan in conjunction with the volute tongue. Therefore, in this work, the draining hole region is also considered as a potential important source regions for BPF nosie, together with the cut-off region near volute tongue.

Hybrid techniques are utilized to analyze noise characteristic of the current centrifugal fan. The hybrid method consists of three steps. First, flow field is calculated through Computational Fluid Dynamics (CFD). Then noise sources are modeled by using the predicted flow field data through acoustic analogy. Finally, acoustic field is predicted by combining the modeling noise sources with the wave equation under the given internal duct boundary condtions. The detailed description on this numerical method is given in Ref. 4.

To predict unsteady flow field generated by the rotating centrifugal fan within the refrigerator, three-dimension incompressibility RANS equations are solved. High Reynolds number k–ε turbulence model is used in order to express turbulent stress. The governing equations are spatially discretized by tetrahedral mesh and are solved by using finite-volume method. To model rotating fan, sliding-mesh method is used. The CFD computations are carried out by using the commercial CFD program, STAR-CD^{TM}. Figure 2-(A) shows surface-mesh of the centrifugal fan system. The centrifugal fan system consists of the fan, its outer case, and the DC motor used to supply power to the fan. Figure 2-(B) shows cross-sectional view of volume-mesh around the centrifugal fan at mid-span of the fan blade. The volume-mesh is classified into rotating grids and stationary grids. Figure 2-(C) displays boundary conditions applied for the prediction of flow field. The constant mass flow rate obtained from the experiment was specified for the inlet region allocated in the upper outmost surface of the mesh. A prescribed pressure boundary is applied at the outlet sections of the other five outmost surfaces. A no-slip wall boundary condition is used on the wall surface of the fan and the fan case. The attached boundary condition is applied at the interface between rotating grids and stationary grids. Unsteady flow computation is continued until periodic flow pattern is observed. After the sixth rotation, periodic fluctuations were observed. Therefore, subsequent flow analysis was carried out using data during the seventh rotation. Figure 3 shows the predicted static pressure contours at the cross-sectional plane of z = 18.0 mm, which corresponds to the middle location in the span direction of the fan blades. Figure 3-(A) to -(D) display the predictions at the beginning, 1/4, 1/2, and 3/4 of the period of the blade passing frequency, respectively. It can be found that the magnitude of fluctuation of the static pressure is higher at the vicinity of draining hole and the cut-off regions near volute tongue. Therefore, these two regions are considered as main noise source regions.

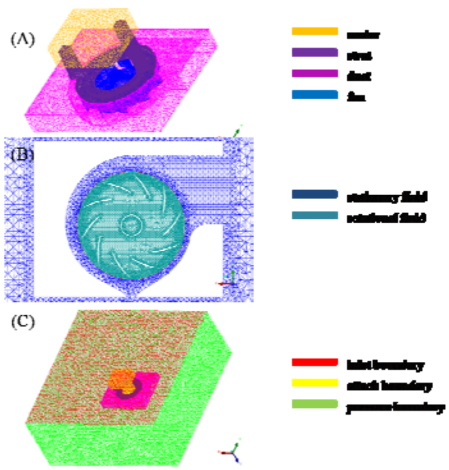


Figure 2. Computation mesh: (A) surface mesh of rigid bodies including the centrifugal fan, (B) volume mesh at the cross-section of mid span location, and (C) boundary conditions applied

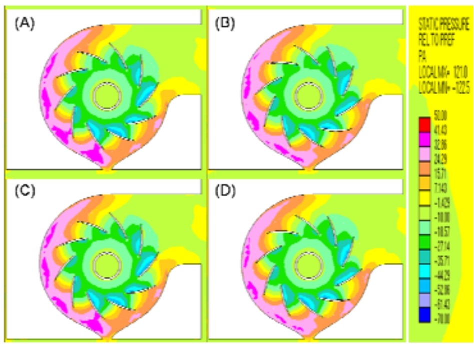


Figure 3. Static pressure contour at the middle cross-section in the span-direction of fan blade: at (A) beginning, (B) 1/4, (C) 1/2, and (D) 3/4 of the period of the blade passing frequency

Quadrupole source modeling was attempted with the velocity data in these regions. Assuming that the viscous stress and the entropy fluctuations are negligible within the moving fluid, the acoustic source terms S_{ij} were modeled using the approximated Lighthill's stress tensor (ALST) as follows [5]:

$$S_{ij,ALST} = -\frac{\partial^2 \rho u_i u_j}{\partial x_i \partial x_j} \quad (1)$$

The two regions near the volute tongue and the draining hole were selected as the maximally contributing source regions whose locations are schematically shown in figure 4. Velarde-Suárez et al. [6] performed a correlation study to identify the source regions responsible for the generation of tonal noise of a centrifugal fan. They showed that the predominant source region was located on the volute tongue surface of the width within 30 degrees (the origin of the angles is located at the volute tongue). The detailed source modelling methods are presented in Ref. [4].

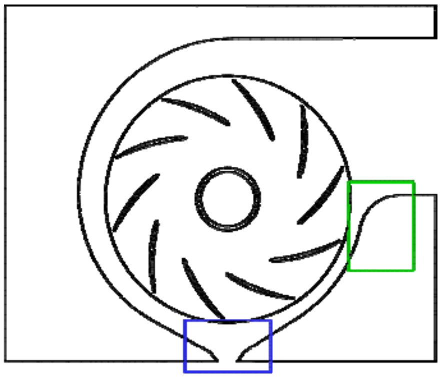


Figure 4. Schematic views of selected main noise source regions

For the prediction of aerodynamic noise from the internal fan flow, the wave equation with the modelled source terms are solved by using Green function which can consider the effect of duct wall on the sound propagation. The Green function is numerically computed through BEM technique. The BEM technique is realized by using commercial program, SYSNOISE^{TM}. Multi-domain BEM method based on direct BEM method is used to treat rigid boundary with openings [7]. First, the internal sound field of the centrifugal fan is predicted through direct interior BEM method. Then the external sound field of the centrifugal fan is predicted by using the information of the internal sound field through direct exterior BEM method. In this process, the open boundary condition is applied on inlet and outlet of the duct case of the fan and region of the draining hole. Figure 5 shows a comparison between measurement result and theoretical prediction. From this comparison, it can be seen that there are good agreements between the predictions and measurements, with maximum difference within 5 dB at the BPF. The potential reason of this difference is that the hybrid method can't consider the interaction between flow and sound fleids. However, the overall trend of the prediction shows satisfactory agreement with the measurement.

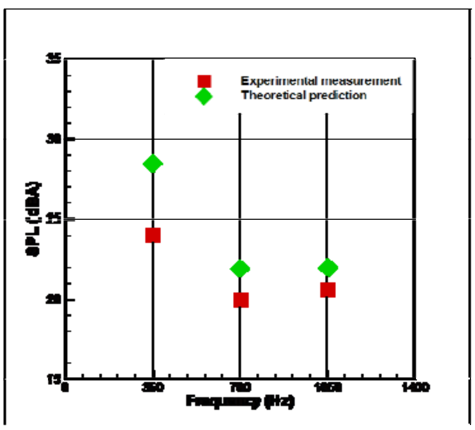
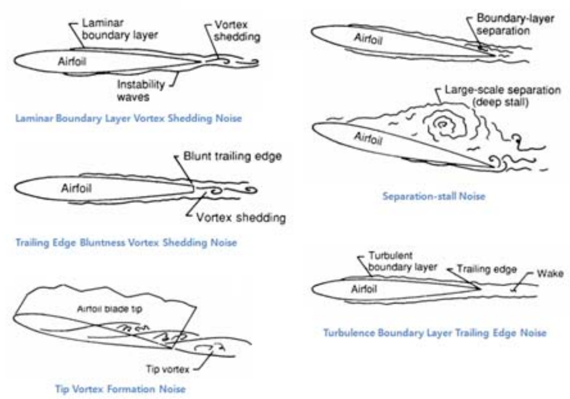


Figure 5. Comparison of the BPF noise levels between prediction and measurement

Low noise centrifugal fan design in the previous work [4], it was shown that the BPF noise was successfully reduced by extending the cut-off region of a centrifugal fan of type similar to the current targeted fan which was already applied with the prescrived BPF reduction measure. It is well known that flow noise from rotating machines such as fans consists of BPF noise and broadband noise. Therefore, for further reduction of centrigual fans, these broadband noise components must be tackled. The broadband noise of fans is classified into two types: inflow noise and self noise. The broadband inflow noise is generated by interaction between incident turbulence and rotating fan blades while the broadband self noise is produced by interaction between turbulent component in boundary layer of airfoil of fan blade and trailing edge of airfoil. However, it is difficult to control the broadband inflow noise by designing the targeted fan only because inflow turbulence depends on the surrounding environment of the installed location of a fan. In this work, therefore, development of low noise centrifugal fans is based on the reduction of the broadband self noise, which exists even in the unrealistic case of laminar inflow without any incident turbulence.



Source: (Brooks et al., 1989)

Figure 6. Noise generation mechanisms of airfoil-self noise

Figure 6 shows the schematics of noise generation mechanisms of airfoil self noise, which was firstly described by Brooks et al. [8]. It can be seen that the four mechanisms of airfoil self noise are due to the interaction of the trailing edge with boundary layer turbulence, except for the tip-vortex noise. Based on this understanding of generation mechanism of broadband self noise, low noise centrifugal fans are devised by inducing phase difference of the potential sources located on the trailing edge lines in the spanwise direction. Fisrt, this concept is realized by inclining the trailing edge, which is expected to induce phase difference in the potential sources of broadband trailing edge as well as in the interaction between the blades and volute tongue, which is known to be dominant source mechanism of the BPF fan noise. Secondly, in addition to this inclination of the trailing edge of the blades, S-shaped trailing edge lines in the span direction are applied to induce additional phase difference for noise sources of broadband self noise. Also, a camber of blade is increased 1.5 times than original model in order to compensate possible decrease of volume flow rate of new fans. The trailing edge of blades is changed into sharper to minimize trailing-edge-bluntness-vortex-sheding noise. Among above described four low-noise design factors; increment of blade camber and sharper shape of trailing edge are applied as common design factors in the following proto types. The angle of inclination and S-shape of trailing edge are considered to be variables for parametric study. Figure 7 show the proto types of low noise centrifugal fans for the parametric study of the selected design factors. The inclination shape is induced by leaning the trailing edge in the rotational direction. S-shape is realized by changing relative position of inclined trailing edge of the blades into S-shaped trailing edges lines. Figure 7-(A) depicts the centrifugal fan that has S-shaped traling edge of maximum depth of 2.5 degree and the inclination angle of 5 degree, which is denoted by 'S025I050 CF' in the following. Figure 7-(B) to-(D) denote the centrifugal fans of S025I100, S050I050, and S050I100. Each of these names represent its own designs as the name means, as above describe: S-shape of 2.5 degree and the inclinantion of 10 degree, S-shape of 5 degree and the inclination of 5 degree, and S-shape of 5 degree and the inclination of 10 degree. For the clear comparison of new fans with the existing fan, Figure-7(E) provides the CAD data of the original fan.

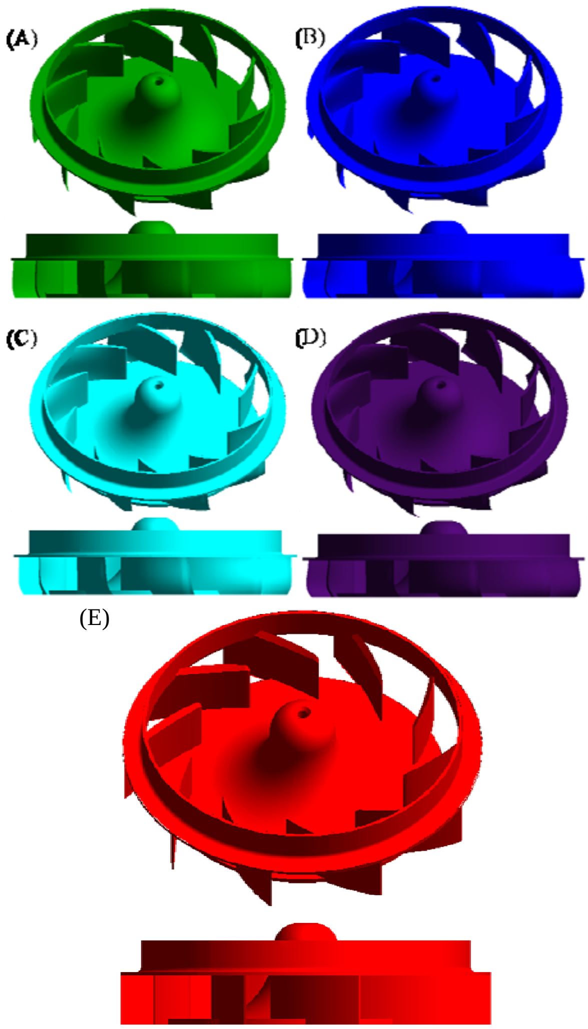


Figure 7. The CAD data of low-noise design fans and the original fan:

COMPUTAIONAL ANALYSIS OF NEW DESIGN FANS

The same numerical procedures as described in the preceding section on the analysis of a targeted fan are applied to assess noise performance of proposed new fans. Figure 8 presents the predicted BPF spectra of the new fans with that of the existing fan. It can be found that noise levels at the fundamental BPF from S025I050, S025I100, S050I050, and S050I100 CFs are predicted to be 3 dBA, 7 dBA, 2 dBA, and 6 dBA less than that of the original fan, respectively. Similar reductions are continued upto fourth harmonics of BPF. It can be inferred from this result that the larger inclination angle induces larger reductions of BPF noise levels. Although it is possible to predict tone noise such as BPF noise by using the hybrid CAA technique based on RANS equations, it is difficult to predict the broadband noise due to the inherent limitation of RANS equations in computing the random behaviour of turbulence, which are believed to be important sources for broadband noise in most of cases. In stead of predicting broadband noise spectrums, therefore, predicted turbulent kinetic energy around fan blades are compared, which are belived to represent the magnitude of broadband noise sources. Figure 9 presents the predicted total turbulent kinetic energy in the flow around fan blades. It can be found that total turbulent kinetic energy predicted for each of new fans is less than that of the existing fan and that the wave shape of 2.5 degree induces larger reduction than that of 5 degree.

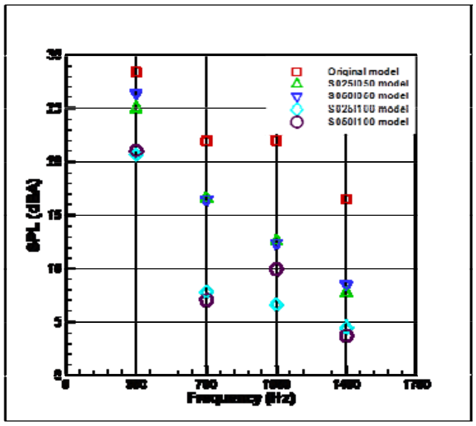


Figure 8. Prediction of low-noise centrifugal fan designs

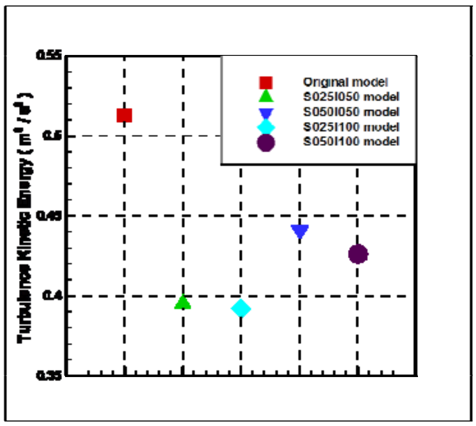


Figure 9. Prediction of turbulent kinetic energy in the duct for each model

EXPERIMENTAL VARIFICATION OF NEW FANS

Based on the result of the previous computational anaylsis, the proto low-noise fans are manufactured to confirm the validity of low-noise design concept. An experiment is performed in the semi-anechoic room. The cut-off frequency of the semi-anechoic room is 125 Hz, and background noise is 16 dB. Figure 10-(A) displays the CAD data of fan assembly used to measure the noise: red solid rectangle denote the targeted fan system and yellow dotted box indicates the axial fan which is not considered in this work. Figure 10-(B) indicates experimental set-up during the measurement. The centrifugal fan is located 0.45m high from the floor, and the measurements are taken at three points 1.2 m apart from the fan at the same height. Figure 11 shows the comparison of measured overall SPLs between the new fans and the original. These results show that the low-noise designs induces the noise reductions by 2 to 3.5 dB in comparison with the original model. These noise reductions are retained over the range of rotation speed of fans from 1800 rpm to 2400 rpm.

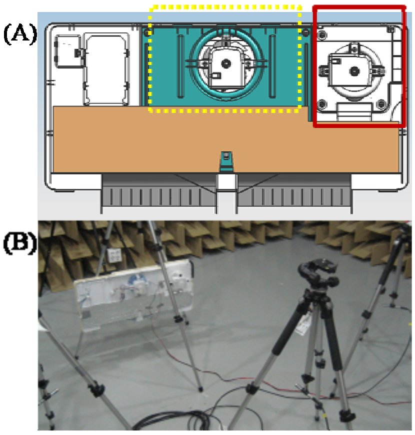


Figure 10. Fan assembly and experimental set up: (A) CAD data of fan system assembly and (B) experimental set up

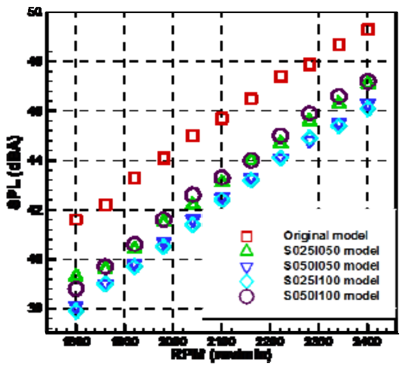


Figure 11. Measure overall SPLs of fans according to its rotating speeds.

CONCLUSION

New kinds of low-noise centrifugal fans are developed by using a novel concept to reduce the airfoil self noise. These new low-noise centrifugal fans are realized by applying the design concepts of inclined S-shaped trailing edge lines with sharper trailing edge than the current fan. First, Validity of newly proposed low-noise fan designs is confirmed through the numerical analysis of its noise performance by using hybrid CAA techniques. Then, noise measurement using the proto types of low-noise fans are carried out, which reveals that overall SPL reduction of 2 to 3.5 dB are achieved in comparison with the original fan over the range of rotation speeds from 1800 rpm to 2400 rpm. Considering the generality of noise reduction mechanism applied in the current study, the proposed low-noise centrifugal fans are believed to be applied not only in the refrigerators but also in many other applications such as air-conditioners and vacuum cleaners.

ACKNOWLEDGMENT

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