Low Noise Design of Regenerative Blower by Combining the FANDAS-Regen Code, Optimization Technique and Phase-Shift Cancellation Concept

Chan Lee, Hyun Gwon Kil and Jun Kon Kim
Department of Mechanical Engineering, University of Suwon, Hwaseong, Korea

Keywords: Regenerative Blower, FANDAS-Regen Code, Optimization Algorithm, Low Noise.

Abstract: Low noise regenerative blower is designed by combining the FANDAS-Regen code and optimization technique. The FANDAS-Regen code used in the present study defines blower design variables on rotating impellers and fixed side channels, and then constructs the 3-D blower design geometry. Based on the designed blower geometry, the FANDAS-Regen code also analyzes the blower performance as well as noise characteristics by using momentum exchange theory coupled with pressure loss and leakage models and by incorporating the performance prediction results into discrete and broadband noise models. With the FANDAS-Regen code as a simulation engine, design optimization is conducted for impeller and side channel design variables to minimize overall sound pressure level of blower under the constraints of aerodynamic design requirements on pressure rise, efficiency and power consumption. Furthermore, for more noise reduction of blower, a staggered impeller blade arrangement as a phase-shift cancellation design concept is also applied to the optimized impeller design. The optimized blower model is manufactured and tested by a chamber-type performance tester and narrow-band noise measurement apparatus. The performance measurement results agree well with the FANDAS-Regen prediction, and the noise measurement results show a remarkable noise reduction of 26 dBA through the present design optimization.

1 INTRODUCTION

Regenerative blowers are usually operated with high pressure rise at low flow capacity and are widely used as the gas supply equipment of fuel cell automotive vehicles and distributed fuel cell power systems (Badami and Mura, 2011; 2012). However, because the most of these fuel cell systems are located very close to human users, when regenerative blower is used in the fuel cell applications, its high noise characteristics would be main shortcoming and hurdle to be applied in the fuel cell applications. For this reason, there are growing industrial needs of low noise regenerative blower design.

Through the previous research by authors(Lee et al., 2013), the FANDAS-Regen code as design-analysis program for regenerative blower has been developed and showed its good prediction accuracies on performances and noise levels of designed regenerative blower. In the FANDAS-Regen code, 3-D blower geometry on impeller blades and side channel is designed, and then blower performances are predicted by the momentum exchange theory between the rotating impeller blades and the fixed side channel. After the predicted performance results are obtained and then incorporated with the noise models of the FANDAS-Regen code, discrete frequency noise at blade passing frequency and its harmonics are predicted by acoustic mode analysis, and broadband noise is also predicted by the combination of several correlation models for inflow turbulence, impeller turbulence and exhaust jet mixing. The performance and noise prediction accuracies of the FANDAS-Regen code are verified by comparing the prediction with the measurement results of actual regenerative blowers.

Furthermore, with the use of the present analysis method of the FANDAS-Regen code as simulation engine, design optimization is conducted for two impeller and side channel design variables to minimize overall noise level of blower, and then a phase-shift cancellation concept of staggered impeller blade arrangement is also applied for more noise reduction of optimized blower. The optimized

Lee C., Kil H. and Kim J..
Low Noise Design of Regenerative Blower by Combining the FANDAS-Regen Code, Optimization Technique and Phase-Shift Cancellation Concept.
DOI: 10.5220/0005514304690475
In *Proceedings of the 5th International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2015), pages 469-475
ISBN: 978-989-758-120-5

blower by the present study is manufactured and tested by using chamber-type test facility and narrow-band noise measurement apparatus and its measurement results are favorably compared with the prediction by the FANDAS-Regen code. The comparison results also show the overall noise level of optimized blower is remarkably reduced by 26 dB(A) when compared with that of initial design.

2 DESIGN, PERFORMANCE AND NOISE ANALYSIS METHODS OF THE FANDAS-REGEN CODE

2.1 Blower Design Method

In general, regenerative blower is composed of impellers equipped on double sides of rotating plate and fixed side channel covering the impellers. Blower's design variables and geometry are shown in Fig.1.

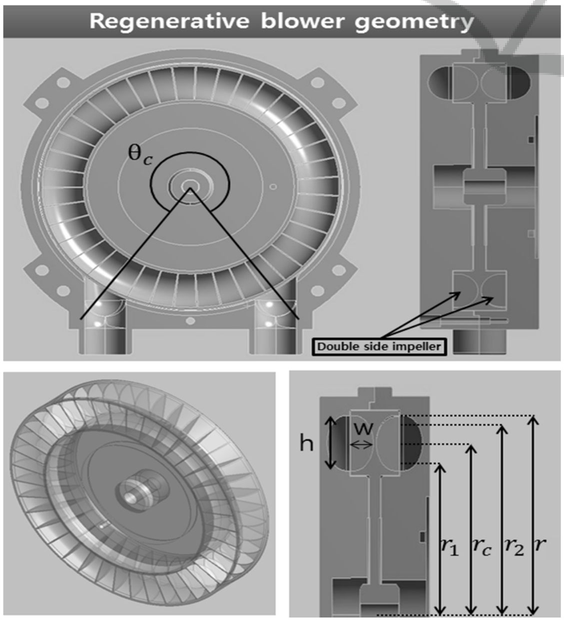


Figure 1: Geometry and design variables of regenerative blower.

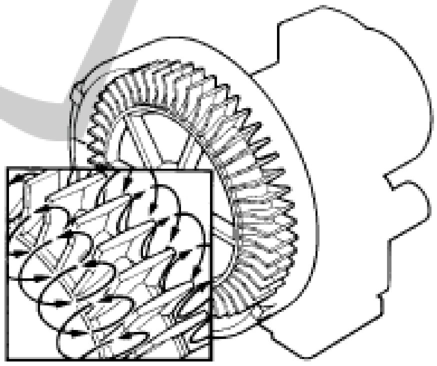
The main design variables of rotating impellers and fixed side channel are defined as follows:

- Rotation speed(N)
- Tip diameter(D_2=2r)
- Channel height(h)
- Channel width(W)
- Impeller blade inlet angle(β_1)
- Impeller blade outlet angle(β_2)
- No. of impeller blades(Z)
- Impeller blade thickness(d)
- Axial clearance(c)
- Extension angle(θ_c)

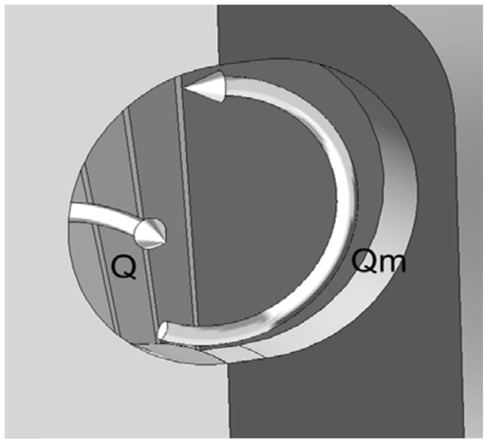
Once the blower design variables are determined by designer, 3-D blower shape and geometry are easily obtained and then can be used for the input data of performance analysis and CFD simulation.

2.2 Blower Performance Analysis Models

In the FANDAS-Regen code(Lee et al., 2013), the performance of blower is analysed by combining the mean line analysis method for fluid flow and the momentum exchange theory between impellers and side channel. As shown in Fig. 2, the gas flow inside regenerative blower is assumed to be typically three dimensional and helical-toroidal motion where fluid rotates in and passes along the space between rotating impeller blades and fixed side channel. The present study assumes mean streamline as the representative one of the three dimensional fluid flow phenomena.



(a) Flow behavior inside regenerative blower



(b) Cross section view on helical-toroidal flow

Figure 2: Flow pattern of regenerative blower.

Through the momentum exchange between fluid and impeller due to this flow motion, gas pressure is gradually raised along tangential flow path and its overall pressure rise(Δp_s) is calculated by

$$\frac{\Delta p_s}{\frac{1}{2}\rho u^2} = 2\frac{Q_m}{A_c u}\frac{r_1}{r_c}\left(\frac{r_2}{r_1}\frac{C_{u2}}{u} - \frac{C_{u1}}{u}\right) - (K_p + K_f/4)\phi^2 \quad (1)$$

where

$$\frac{C_{u2}}{u} = \frac{r_2}{r}\left(1 - \frac{\Delta u_2}{u_2}\right) + \frac{A_c}{A_2}\left(\frac{Q_m}{A_c u}\right)\cot\beta_2 \quad (2)$$

$$\frac{\Delta u_2}{u_2} = \frac{1.5 + 1.1(2 - 2\beta_2/\pi)}{Z[1 - (r_1/r_2)^2] + 1.5 + 1.1(2 - 2\beta_2/\pi)} \quad (3)$$

$$\varphi = \frac{Q}{u A_c} \quad \frac{C_{u1}}{u} = \frac{r_1}{r}\varphi \quad (4)$$

$$\frac{1}{2}\left[K_m + \frac{1}{\sin^2\beta_2} + \left(\frac{A_2}{A_1}\right)^2\cot^2\beta_1\right]\left(\frac{A_c}{A_2}\right)^2\left(\frac{Q_m}{A_c u}\right)^2 + \left(\frac{r_1}{r} - \frac{u_{c1}}{u}\right)\cot\beta_1\frac{A_c}{A_1}\left(\frac{Q_m}{A_c u}\right)_2 + \frac{1}{2}\left[\frac{r_1^2 - r_2^2}{r^2} + \left(\frac{u_{c2}}{u_1}\right)^2 - \left(\frac{u_{c1}}{u}\right)^2\right] = 0 \quad (5)$$

Here ρ, u, Q, Q_m and φ are fluid density, impeller rotation speed, flow capacity, circulating flow rate and flow coefficient. More detailed description and variable definition about momentum-exchange theory are referred to Badami et al(Badami and Mura, 2012).

As represented in equation (1), proper models for pressure losses and the leakage flows should be constructed for accurate performance prediction, so the FANDAS-Regen code uses the correlations of Table 1, which are expressed as the functions of blower design variables(Lee et al., 2013).

Table 1: Pressure loss and leakage model coefficients.

Related flow phenomena	Present model	Reference
Circulating flow loss(K_m)	$K_m = f(A_c/A_{cir}) = f(h,W)$	Choi et al.(2003)
Tangential flow loss(K_p)	$K_p = 0.0175 f_p(\mathrm{Re}_{D_h})\theta_c\frac{r_c}{D_h}\left(0.7+0.35\frac{\theta_c}{90}\right)\left(0.21\frac{1}{(r_c/D_h)^{0.25}}\right)$	Handbook of hydraulic resistance
Entry and discharge flow losses(K_L)	$K_L = \left(0.95\sin^2(135-\frac{\theta_c}{4}) + 2.05\sin^4(135-\frac{\theta_c}{4})\right)\left(0.95+\frac{33.5}{270-\theta_c/2}\right)$	Handbook of hydraulic resistance
Casing-impeller leakage flow(K_{f1})	$K_{f1} = \frac{1.4(1+0.01Rv^2)}{\mathrm{Re}_{D_h}^{0.1}(r/c)^{0.25}}$	Kang & Lim(2005)
Stripper leakage flow(K_{f2})	$K_{f2} = f_p(\mathrm{Re}_{D_h})\frac{L_c}{D_h}$	Kang & Shim(2003)

2.3 Blower Noise Modelling and Analysis Method

Based on the blower performance prediction results, the FANDAS-Regen code considers two kinds of noise components. One is the discrete frequency noise at blade passing frequency(BPF) and another is the broadband noise distributed over wide frequency range, which are produced due to inflow turbulence at blower inlet, turbulence within impeller and side channel and turbulent jet at blower exit.

Discrete frequency noise is produced due to the pressure difference between adjacent impeller blades rotating at BPF. In the present study, the pressure difference is defined by $\Delta p_s/Z_e$ or $2\Delta p_s/Z_e$ and its pressure fluctuation can be modelled as shown in Fig. 3:

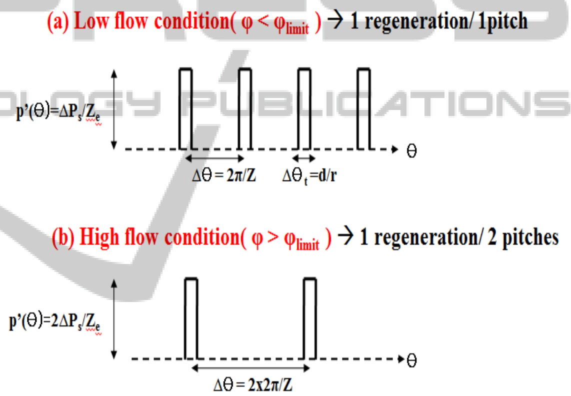


Figure 3: Theoretical model for the pressure fluctuation between adjacent impeller blades.

where Δp_s is overall blower pressure rise calculated by the performance prediction method of section 2.2, and Z_e, d and r represent effective number of impeller blades, impeller thickness and impeller tip diameter respectively, and θ is angular coordinate in the direction of tangential flow. As shown in Fig. 3, fluid pressure rise is achieved through 1 regenration/1 pitch of fluid at low flow capacity($\varphi < \varphi_{lim}$) while it being achieved through the 1 regeneration/ 2 pitches at high flow capacity($\varphi > \varphi_{lim}$). Here φ is the flow coefficient as non-dimensional flow capacity parameter, and φ_{lim} is assumed as 0.75 from the experiment of Badami and Mura(Badami and Mura, 2013).

Under the assumption of dipole type noise radiation, classical acoustic theory (Wright, 1975) on the rectangular-shaped pressure fluctuation of Fig. 3 gives the following root mean square value of acoustic pressure(p_a') as:

$$p_a'(R,\theta) = 2\sqrt{2}\left(\frac{\Delta p_s r}{mZ\ \theta_c}\right)\sin\left(\frac{mZd}{2r}\right)\frac{\cos(\ mZ\ \theta)}{R}$$

at $\varphi < \varphi_{\lim}$

$$p_a'(R,\theta) = 4\sqrt{2}\left(\frac{\Delta p_s r}{mZ\ \theta_c}\right)\sin\left(\frac{mZd}{2r}\right)\frac{\cos(\ mZ\ \theta)}{R}$$

at $\varphi > \varphi_{\lim}$

(6)

where m= 1 means fundamental mode, m=2,3, … mean its harmonic modes, and θc, θ and R are side channel extension angle, noise measuring angle and radius.

Broadband noise is produced from three main noise sources of inflow turbulence, impeller turbulence and exhaust turbulent jet. The present study employs well-verified correlation model corresponding to each noise sources (Mugridge, 1976; Goldstein, 1976), and their noise prediction results are superimposed over frequency range. It is noted that all the present broadband noise models are expressed in terms of blower design variables and performance parameters.

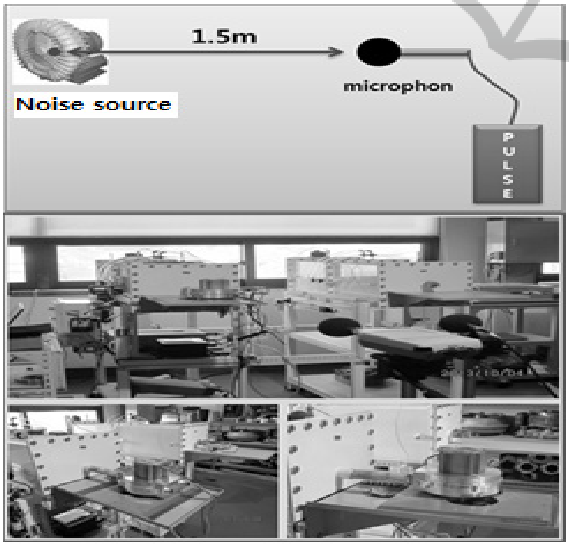


Figure 4: Performance and noise measurements.

2.4 Verification of the FANDAS-Regen Code Prediction Method

The FANDAS-Regen code is applied to two existing blower models for verifying its prediction accuracies of performance and noise. The performance and noise measurements on two Hwang-Hae blower models (Hwang-Hae, 2012) are made by chamber-type test facility and by the precision sound level meter or the PULSE, a FFT analyser, as shown in Fig. 4.

Figs. 5 and 6 show the performance and the noise prediction results of Mini H-200 model(Hwang-Hae, 2012)by the FANDAS code. The performance prediction results are well-agreed with the measurement over entire flow capacity range, and the noise spectrum analysis result derived from the performance prediction is also verified through the good comparison between the prediction and the measurement at blade passing frequency and over wide frequency range. It is noted the noise measurement of Mini H-200 at maximum flow capacity is made from octave band analysis at 1.5 m from blower inlet.

Fig. 7 and 8 represent the comparison between the FANDAS-Regen code and the measurement results of Mini H-100 model(Hwang-hae, 2012). As shown in Fig. 7, the predicted performances by the FANDAS-Regen code are well-agreed with the measurement. Fig. 8 shows the predicted noise spectrum at maximum flow capacity is reasonably agreed with the 1/3 octave band measurement.

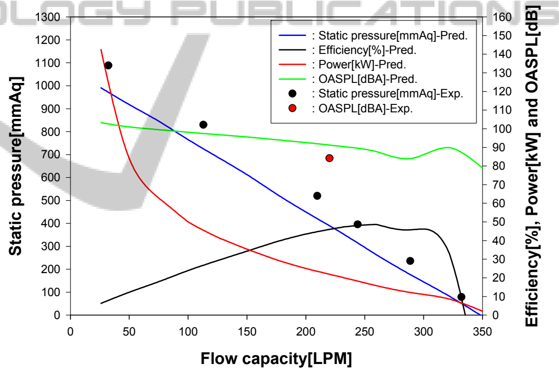


Figure 5: Aero-acoustic performance map of Mini H-200.

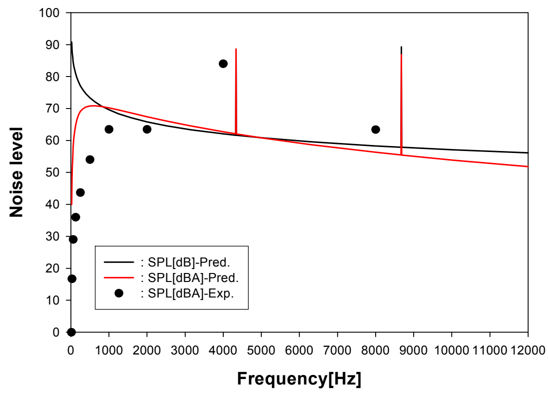


Figure 6: Noise spectrum of Mini H-200.

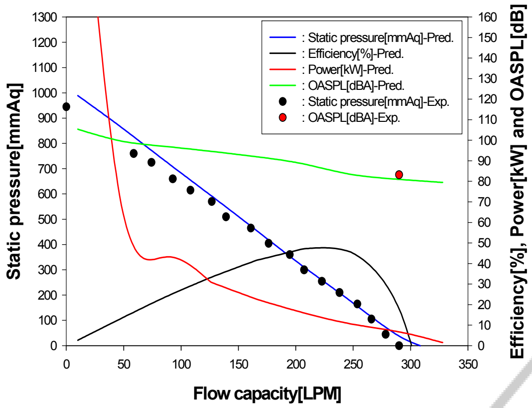


Figure 7: Aero-acoustic performance map of Mini H-100.

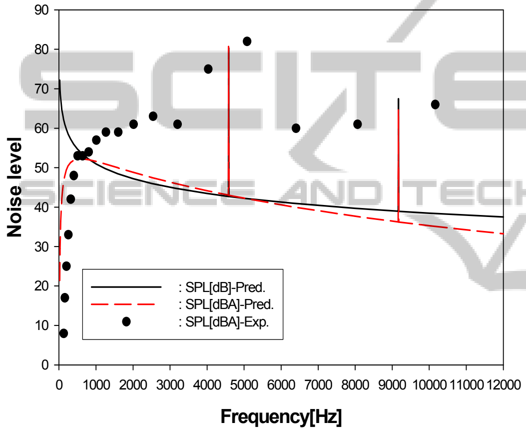


Figure 8: Noise spectrum of Mini H-100.

From the comparison results of Figs. 5-8, the performance and noise prediction method of the FANDAS-Regen code is expected to be used as reliable simulation engine suitable for blower design optimization.

3 BLOWER NOISE REDUCTION BY DESIGN OPTIMIZATION

The present study conducts design optimization for noise minimization of the blower with the following design parameters:

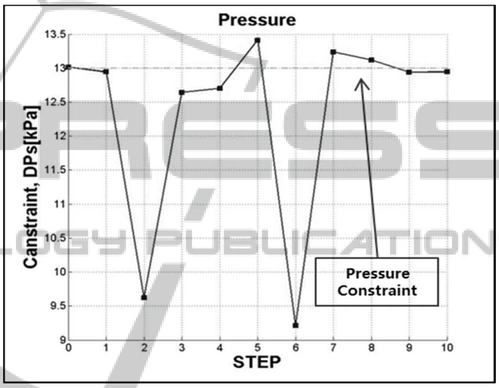
- Rotation speed = 7400 rpm
- Side channel height(h) = 20 mm
- No. of impellers(Z) = 39
- Axial clearance(c) = 0.2 mm
- Impeller blade thickness(d) = 1 mm
- Tip diameter(D_2) = 100 ~ 200 mm
- Side channel width(W) = 5 ~ 15 mm

As mentioned above, tip diameter(D_2) and side channel width (W) are treated as the design variables of optimization study while the other parameters being as fixed values.

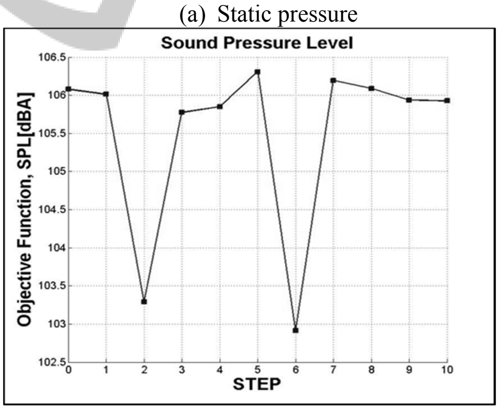
Therefore, the present optimization problem can be formulated with the constraints for design requirements as follows:

Find D_2 and W to minimize OASPL[dBA]

Subject to design flow capacity(Q_d) = 350[LPM]
design pressure(ΔP_s) ≥ 13 [kPa]
design-pt. efficiency(η_s) ≥ 25 [%]
design-pt. power ≤ 500 W



(a) Static pressure



(b) Overall sound pressure level

Figure 9: Solution-finding histories.

The above optimization problem is solved by the STQDAO algorithm of gradient-based sequential approximate optimization technique in the PIAno code (PIDOTECH, 2013) and its solution-finding histories are shown in 9. After 10 iterations from initial design condition, with satisfying pressure constraint, optimum design is obtained as D_2 = 144 mm, W = 12 mm and results in the noise reduction by 2.78 dBA compared with the initial design.

In addition to the optimization mentioned before, for more noise reduction, the present study also employs a phase-shift cancellation concept on impeller blade arrangement design. As known from Fig. 3 of section 2.3, acoustic pressure is radiating from each impeller blade in the form of sinusoidal wave with the period of blade pitch. Thus, because impeller blades are equipped and arranged along angular direction on double sides of rotating plate, if the impeller blades are arranged with staggered type as shown in Fig. 10, the acoustic pressure radiating from impeller on one side could be cancelled by that from impeller on another side (Lee and Kil, 2014; Kim et al., 2014).

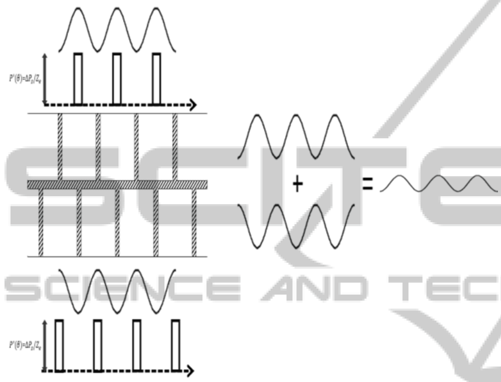


Figure 10: Phase-shift cancellation concept.

Fig. 11 shows the pressure rise curves of the blower model obtained through the applications of design optimization and phase-shift cancellation concept. The predicted pressure curves are well agreed with the test ones at various RPM conditions, and the optimized model satisfies its design requirement of static pressure at design point.

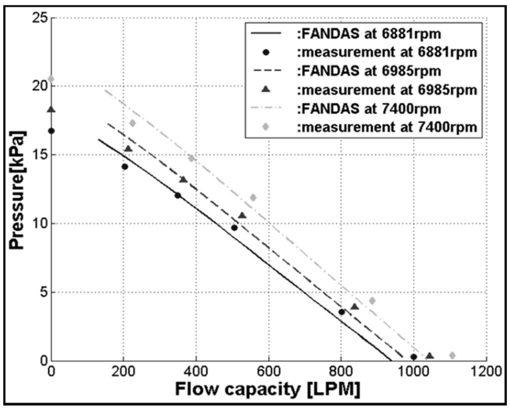


Figure 11: Pressure rise curves of optimized blower.

Fig. 12 shows the comparison of the predicted noise spectrum of initial blower model with the measured one of the optimized blower model. As shown in Fig. 12, remarkable noise reductions of discrete frequency noise components can be found at BPF and its harmonics. These noise reduction effects might be due to both the design optimization of 2.78 dBA and the phase-shift cancellation of 22.9 dBA. The overall sound pressure level of the optimized blower is significantly reduced by about 26 dBA compared with the initial design case.

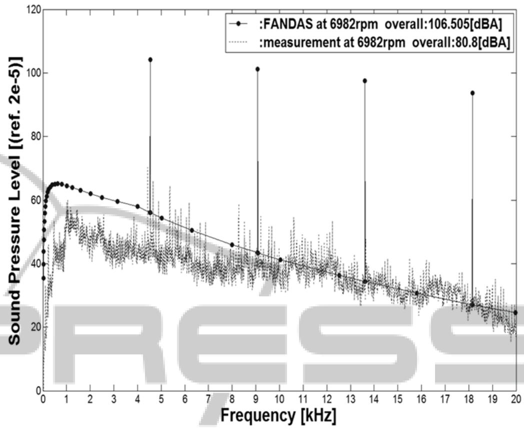


Figure 12: Noise spectrum of optimized blower.

4 CONCLUSIONS

The present study conducts noise reduction design of regenerative blower by combining the FANDAS-Regen code, optimization technique and phase-shift cancellation concept. The FANDAS-Regen code, as simulation engine of optimization problem, can predict blower performances as well as noise levels and its prediction results are well agreed with the measurements. The optimization process by STQDAO algorithm is carried out for low noise blower design and then phase-shift cancellation concept of staggered impeller arrangement is also applied to the optimized blower. The present design optimization gives the final design with 26 dBA noise reduction compared with the initial design.

ACKNOWLEDGEMENTS

This work was supported by the Development of the Regenerative Blower for fuel cell application of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES

M. Badami, and M. Mura, Comparison between 3D and 1D Simulations of Regenerative Blower for Fuel Cell Applications, 2012, *Energy Conversion and Management*, 55, 93-100.

C. Lee, H.G. Kil, G.C. Kim, J.G. Kim, J.H. Ma, and K.H. Chung, 2013, Aero-acoustic Performance Analysis Method of Regenerative Blower, *J. of Fluid Machinery(in Korean)*, 16(2).

M. Badami and M. Mura, 2011, Setup and Validation of a Regenerative Compressor Model Applied to Different Devices, *Energy Conversion and Management*, 52, 2157-2164.

S. E. Wright, 1976, The Acoustic Spectrum of Axial Flow Machines, *J. of Sound & Vibration* 45(2), 165-223.

B. D. Mugridge, 1976, Noise Characteristics of Axial and Centrifugal Fans as Used in Industry, *Shock and Vibration Digest*, 45(3).

M. E. Goldstein, 1976, Aeroacoustics, McGraw-Hill. *Regenerative Blower Performance and Noise Test Report*, 2012, Hwang Hae Electric Co.

PIAnO(Process Integration, Automation and Optimization user's Manual, Ver.3.5, 2013, PIDOTECH, INC.

C. Lee and H.G. Kil, 2014, Impeller for reducing noise and regenerative blower with the same impeller, *Korean Patent No.1014593790000.*

J. K. Kim, K. Y. Lee, C. Lee , H. G. Kil, K. H. Chung and S. M. Hwang, 2014, Development of a low-noise regenerative blower for fuel cell application, *The KSFM Journal of Fluid Machinery*, 17(2), 48-53.