Technical Paper

Research and Development of Ring Fan

Haruhiro Tsubota

Noise sources of construction machinery are diesel engines and cooling fans. Recently, a large air flow is also desired to meet exhaust gas regulation in addition to an increase in the cooling capacity of fans.

Several years ago, "visualization" of a fan noise source was attempted by analyzing the fluid noise of fans jointly with a university. The analysis showed that eddies at the tips of fan blades were one factor in the production of noise. Research and development of a ring fan, which was found to be effective in curbing blade tip eddies, was conducted. In the initial stage of the research, it was examined whether or not a ring fan used in buses and trucks sold on the market could be used. The fans available on the market at that time were not suitable as they were for such purpose and a ring fan featuring both performance and strength suitable for use in construction machinery was developed. At present, the ring fan is already in mass production for use in compact wheel loaders.

The new ring fan will be used in other Komatsu products in series. The features of the ring fan are described.

Key Words: *Ring fan, Construction machinery, Low noise, Eddy at tips of fan blades, Exhaust gas regulation, Heat balance, LES, Noise regulation*

1. Introduction

In response to the mounting calls for environmental protection, Tier 4 exhaust gas regulation will be enforced beginning 2011. To clear the Tier 4 regulation, heat radiation is forecasted to increase 20 to 30% compared with Tier 3 due to deterioration of heat rejection. A higher cooling capacity and an increase in cooling air volume are needed to solve this problem.

Ambient noise regulations (EU Tier 2 and Japanese low noise regulation) are also continuously enforced as environmental regulations. Additionally, a reduction of the noise at the operator's station is also desired to enhance the product features. Unlike automobiles, buses and trucks, construction machinery especially cannot expect to have a headwind and a large amount of artificial air for a cooling fan is needed to maintain a proper heat balance. An analysis of contribution factors of construction machinery by ambient noise shows that generally the fan and engine are the two largest noise sources (**Fig. 1**).

A low-noise cooling fan is strongly desired to solve these two contradicting noise problems.

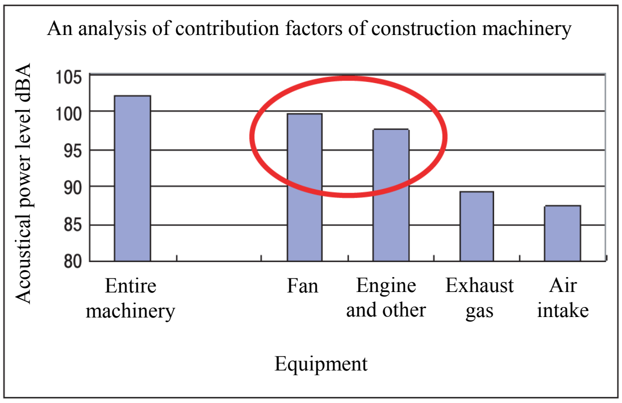

Fig. 1 Example of noise contributing factors of construction machinery

In the past, techniques to absorb and shield sounds shown in **Fig. 2** have been focused as techniques to reduce noise. Due to technical difficulties, measures on sound sources have been lagging. Nevertheless, these measures are needed for optimum usage of the equipment and enhance the balance of the entire machine body, ultimately improving the efficiency as well.

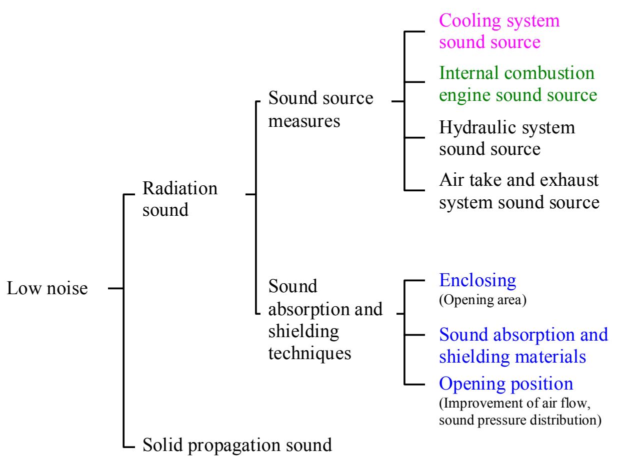

Fig. 2 Techniques for reducing noise of construction machinery

2. Grasping of Current Status of Cooling Fan and Problems

The diameters of the fans adopted in the construction machinery of Komatsu are mostly 600mm. The number of fans installed in construction machinery is one or two digits smaller compared with fans installed in automobiles. High-performance fans require 3-dimensional blades and the depreciation cost of dies for fans increases the cost of construction machinery. Research of fans of new shapes has not been active because of a low production volume of fans.

A forecast of an optimum 3-dimensional blade shape for a high-performance fan of low noise and large air volume by calculation is not feasible and calculations are currently made empirically. Performance of a blade of a blade shape that is already existing can be calculated, but the current technology level is not high enough yet to calculate an optimum solution by inverse calculation. LES (large eddy simulation) is one of the state-of-the-art fluid noise simulation methods, but quantitative verification of it has not been performed yet. Some results of joint research undertaken by Komatsu with a university several years ago have been reported. The level of the research is such that calculations were made using LES. The reader is invited to read Reference 1) "LES analysis of non-steady flow inside propeller fan" for more information. An ordinary propeller fan was measured 3-dimensionally and the blade shape was modeled (**Fig. 3**).

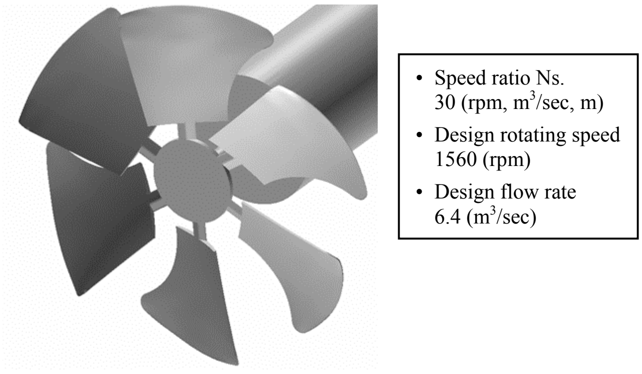

Fig. 3 Propeller fan

- Analysis region
  Number of total elements: 4 million (Region near fan: 3 million) (**Figs. 4** and **5**)

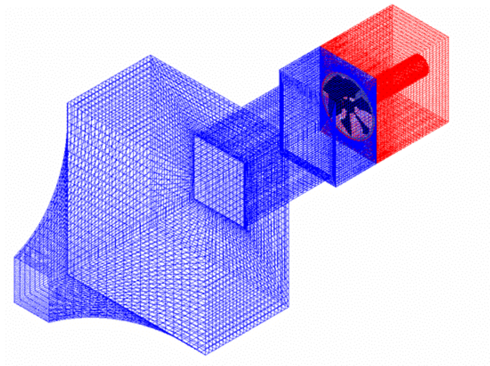

Fig. 4 Entire area of analysis

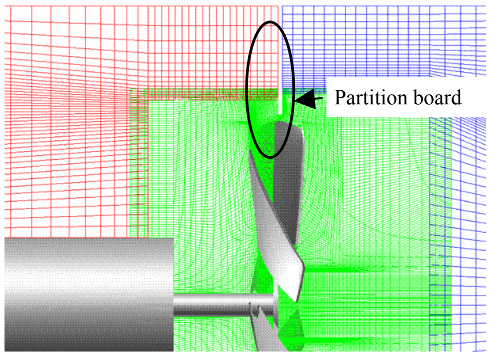

Fig. 5 Region near fan

Calculation conditions			
	85%	100%	115%
Flow rate (m^3/sec)	5.5	6.4	7.4
Representative length	Dt = 850 (mm)		
Representative speed	u2 = 69.4 (m/sec)		
Reynolds number	$Re = Dt \cdot u2/\nu = 5.6\times10^6$		
Calculation pitch time	$\Delta t = 3.14\times$E-04		

These conditions were calculated by LES using a standard Smagolinski model. The characteristic curve (P-Q curve) well matched three points in actual measurement (fan varies draft resistance at same rotating speed: Flow rate 85%, 100%, 115%) (**Fig. 6**).

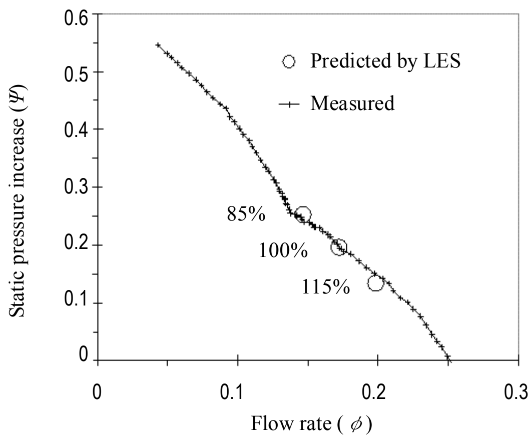

Fig. 6 Characteristic curve (P-Q curve)

Fig. 7 plots pressure fluctuations and flow pass on the surfaces of a fan. At a flow rate of 85%, interference with the next blade of the eddy is large, with pressure fluctuations becoming a secondary sound source and increasing noise. In fluidity noise forecast, which is the purpose of this research, the Powell sound source distribution was calculated from a distribution of eddies generated using the following calculation formula. The result of the calculation is shown in **Fig. 8**. An eddy generated on the positive pressure plane of the blades moves to the negative pressure plane (rear side) at tips of the fan blades. The distribution increases larger the large noise level is (already confirmed in an experiment).

■ LES calculation formula by standard Smagolinski model.

$$\frac{\partial}{\partial x_i}\bar{u}_i = 0$$

$$\frac{\partial}{\partial t}\bar{u}_i + \frac{\partial}{\partial x_j}\bar{u}_i\bar{u}_j = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) - \overline{u'_i u'_j}\right)$$

$$\nu_{SGS} = (Cs\Lambda)^2\left(2\bar{S}_{ij}\cdot\bar{S}_{ij}\right)^{0.5} \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

■ Lighthill equation

$$\left(\frac{\partial^2}{\partial t^2} - a^2\frac{\partial^2}{\partial x_j^2}\right)\rho = \frac{\partial^2}{\partial x_i \partial x_j}T_{ij} \qquad T_{ij} = \rho u_i u_j + \left(p - a^2\rho\right)\delta_{ij} + \mu_{ij}$$

$$\mu_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial u_k}{\partial x_k}$$

- High Reynolds number, heat is not accompanied
- Density gradient, small time change
- Low Mach number

■ Powell sound source calculation formula

$$\left(\frac{\partial^2}{\partial t^2} - a^2\nabla^2\right)\rho = \nabla\cdot\left(\rho\vec{\omega}\times\vec{u}\right)$$

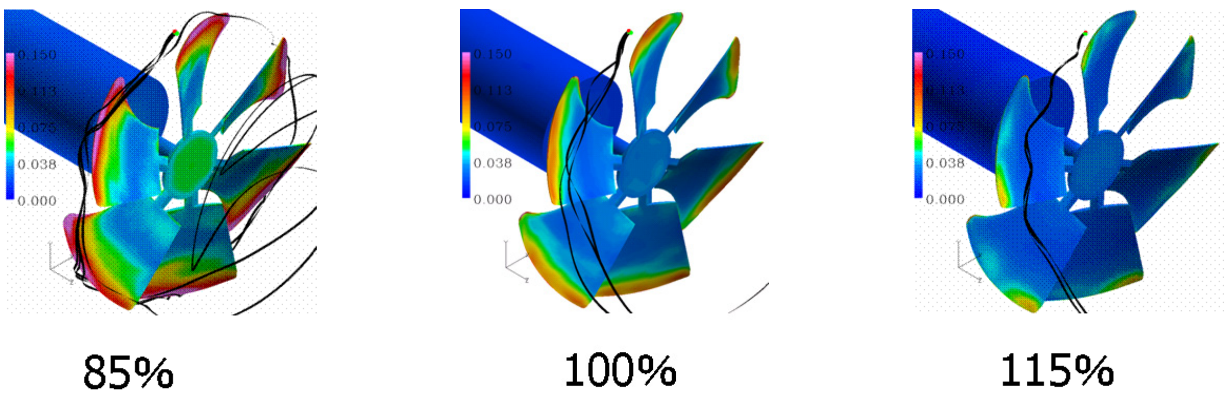

Fig. 7 Fluctuations of fan surface pressure and flow pass

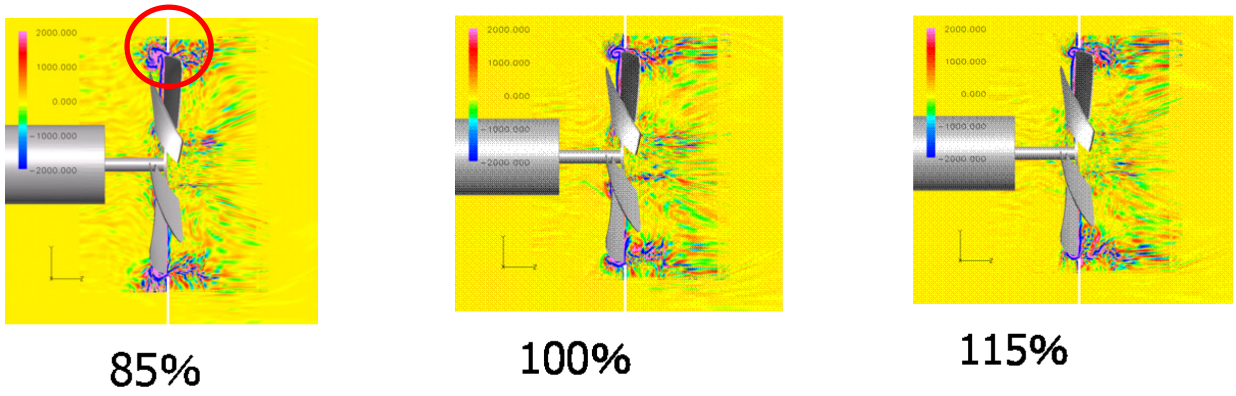

Fig. 8 Distribution of Powell sound source

3. Measures for Solution of Problems of Existing Fan (Ring Fan)

As measures to reduce noise of the cooling system, the rotating speed has been controlled by improving the shroud shape, by making the blades sweepforward blades and by driving by a hydraulic motor. However, research and development of ring fan was undertaken to mainly curb an eddy at tips of fan blades based on the result of Powell sound source distribution mentioned above.

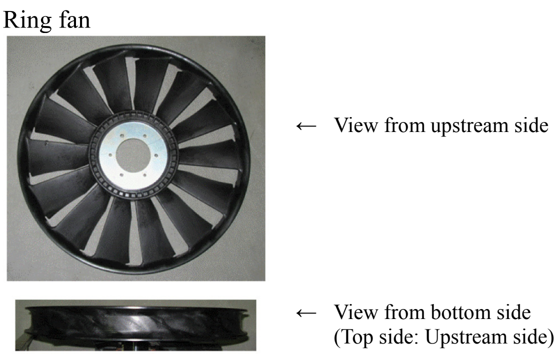

Fig. 9 Ring fan

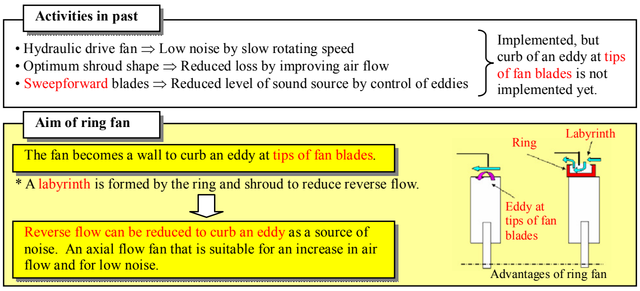

Fig. 10 Activities in past and aim of ring fan

The so-called ring fan (also called a fan with shroud ring) is a generic name for fans that have a ring at the tip of a fan (**Fig. 9**). The shape of the ring fan is varied. This research, however, has selected the shape of "コ" facing upward, which has a large modulus of section and which assures a strong mechanical strength (**Fig. 10**).

1) The principal function of the ring fan is a curb on an eddy at tips of fan blades. In the case of construction machine especially, a difference in static pressure exists between the upstream and downstream sides, causing a large air flow component in a centrifugal direction. Skillful processing of the air flow at tips of fan blades greatly affects enhancement of the air flow efficiency and a curb on noise caused by an eddy at tips of fan blades.
Tilting of the air flow direction of the downstream side (outlet side) in a centrifugal direction when the draft resistance is large is illustrated in **Fig. 11**.

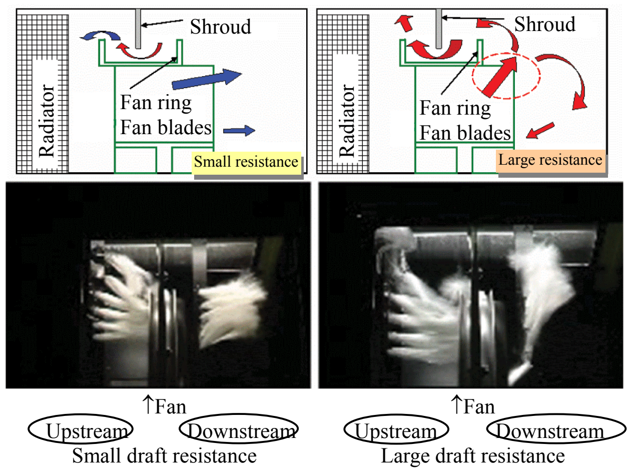

Fig. 11 Differences in draft resistance and in air flow direction of the downstream side.

2) The auxiliary function is a structure that sets the tip clearance, which is effective in reducing the reverse flow at the tips of the blades where the work is done most, to "0."

(**Fig. 12**) Some motorcycles have ring fans without a shroud. The clearance between the ring and shroud can also be considered as a second tip clearance, but is secondary. A variety of structures have been proposed to form a labyrinth and to change the reverse flow by changing the shapes of the shroud and ring.[2] In the application for construction machinery, however, the cost effectiveness is small. Visualization of air flows by a smoke or a tuft has shown that air flows flow in reverse.

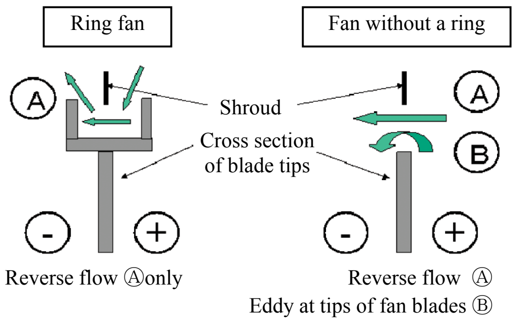

Fig. 12 Mechanism to reduce reverse flow

3) Impacts of shroud overlapping ratio and ring width

It is important to ensure that air exiting from the fan is exited to the outside of the shroud. Air cannot exit to the outside if the draft resistance is large even though the overlapping ratio is the same (**Fig. 13**). Similarly, an optimum value exists also with the width of the ring that curbs an eddy at tips of fan blades. If the width is too wide, the air flow is retarded and the air flow is reduced. In the beginning, the width was set at about 2/3 of the blade size. However, recently, a slightly wide ring width is popular with fans for construction machinery (small draft resistance) (**Fig. 14**).

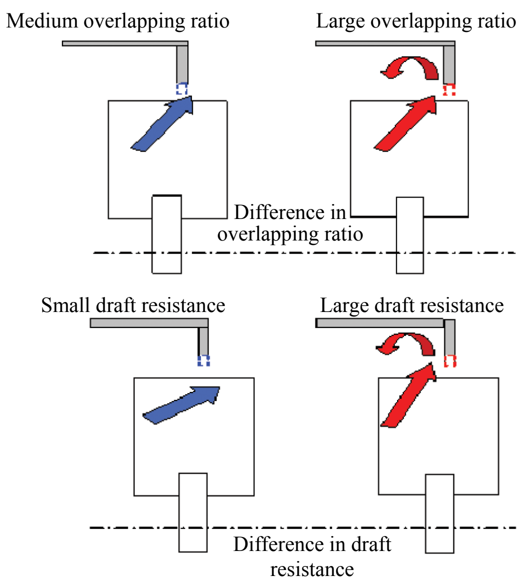

Fig. 13 Impacts by overlapping ratio and draft resistance

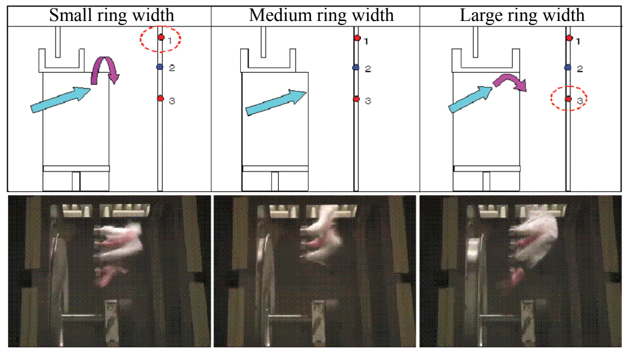

Fig. 14 Differences in ring width and air flow

4. Anticipated Problems of Ring Fan and Remedies

1) Verification of durability (Verification by FMEA)

The ring fan will be a new fan for Komatsu and a quality verification study meeting was convened among the departments concerned. At the meeting, an FMEA chart summarized in **Table 1** was prepared and was studied.

Table 1 Part of FMEA chart for ring fan

Design Quality Verification Sheet (FMEA)

No.	Function, performance	Failure mode	Estimated cause	Design characteristics	
	Durability, performance				
	Durability	Damage	Burst, unable to rotate	Allowable burst rotating speed Rotating speed at high idling speed	
	Durability	Whitening and other anomalies	Lack of durability at high temp.	Allowable high-temp. durable rotating speed	Test peripheral speed Continuous durability time Ambient temp. (No anomalies allowed)
	Durability		Lack of durability against vibration	High-temp. vibration durability test	Vibration frequency Resonance frequency Ambient temp. Excitation table acceleration
	Performance		Lack of stress	Stress test	Max. allowable frequency Allowable stress to resin parts
	Durability	Cracking, whitening and other anomalies	Lack of fatigue strength	Rotating fatigue test	Test stress Max. stress generated Number of iterative stresses
	Performance		Lack of strength at low temp.	Low-temp. falling ball test	Ambient temp. Impact value (No anomalies allowed)
	Durability	Wear due to dust	Large amount of wear	Wear test	Type of sand Test time
	Performance	Deformation at high temp.	Large deformation at high temp.	High-temp. deformation verification test	Ambient temp. Test peripheral speed Max. allowable peripheral speed Clearance with nearby parts 10mm
	Durability	Cracking, whitening and other anomalies	Lack of strength on engine stand	Durability test on engine stand	Test time (No anomalies allowed)
	Durability	Cracking, whitening and other anomalies	Lack of strength in field test	Field test in real vehicle	Test time (No anomalies allowed)
	Performance	Vehicle overheat, high vehicle dynamic noise	Unit performance not accomplished	Fan wind tunnel test	Air flow Noise Horsepower consumption
	Durability	Damage	Lack of balance	Balancing, mud attached	Amount of mud attached Fracture rotating speed

Especially as a characteristic of the ring fan, a ring is attached onto the peripheral of the fan and the blades are supported "inboard," relaxing stresses applied to the bases of the blades. Rattling of the blades is reduced and good trends are shown in noise and air flow also. As one disadvantage, the centrifugal force increases and stresses at the tips of the fan blades become large. (Moment of inertia increases, relaxing rotating speed fluctuations and providing advantages in noise and strength also). The fracture rotating speed by centrifugal force was calculated by FEM and the strength is verified in a vacuum fracture rotating speed test (**Fig. 15**).

In the case of ring fans in construction machinery, they will be used in a more rugged condition compared with ring fans already sold on the market and installed in buses, trucks and automobiles. The strength of the ring fan has to be increased to avoid damage in such rugged condition. Komatsu has been verifying quality anticipating an unbalance due to, for example, earth and sand.

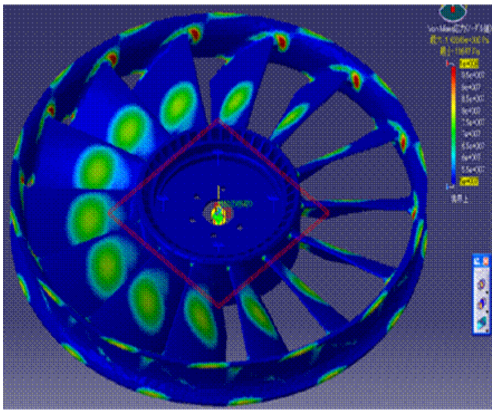

Fig. 15 Example of fracture rotating speed calculation by FEM

For example, the number of blades is increased to lessen the burden of a centrifugal force applied to each blade as a measure to enhance the fan strength. As a result of a verification test of performance and strength without changing the pitch/code ratio, the number of blades has been increased to 14 compared with 7 as before (**Fig. 16**).

Additionally, the corner radii at the tips of the blades, which structurally receive large stresses, were increased without affecting the performance (**Fig. 17**).

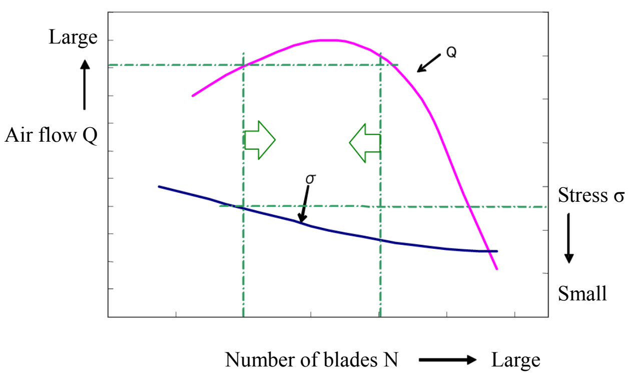

Fig. 16 Relationship between number of blades and air flow/stress

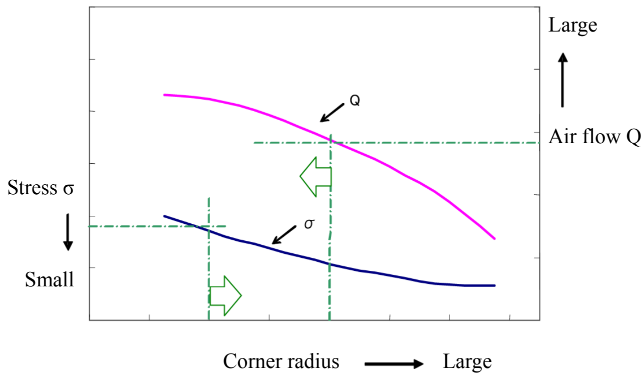

Fig. 17 Relationship between corner radius and stress/air flow

2) Selection of manufacturing method
The centrifugal force component of the ring fan became large and various forming methods were studied. As a result, injection molding of resins was selected. As the material, glass fiber is generally mixed in a nylon resin. The problem was with reinforcement of welded areas. In the welded areas, glass fiber does not act as a bridge and reinforces the base metal. A countermeasure on the shape was needed and optimum values were found after repeating FEM calculations of the wall thickness and corner radii of the welded areas.

3) Usage in construction machinery
As mentioned earlier, the difference in static pressure of the upstream and downstream of the fan is large. For this reason, air flows diagonally to the rear (60° to 75°) relative to the shaft even with the propeller (axial flow) fan. Originally, it is better for air to flow in an axial direction as in electric fans. The angle can be smaller if draft resistance can be reduced.
For this reason, a structure without an obstacle in the downstream of the fan is preferable. The flow in the upstream should preferably have less disturbances. A grille cooling assembly is preferable. Recently, more fans driven by a hydraulic motor are installed compared with engine driven fans in the past. Fan types that have a structure to open the downstream side to the atmosphere are increasing, placing the fan in a position that can be seen from the outside. This is why a low noise fan is desired (**Fig. 18**).

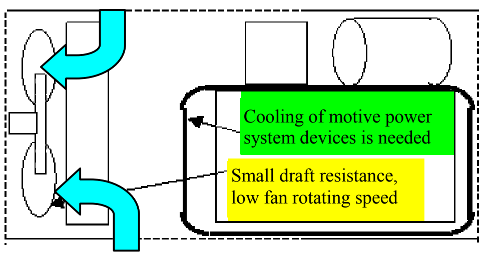

Fig. 18 Example of layout of cooling assembly

4) Results of bench measurement and actual machines
The ring fan was installed in a wind tunnel bench illustrated in **Fig. 19**. The performances of a conventional fan and the ring fan are compared in **Fig. 20**. Compared with a conventional fan, the ring fan improves noise by 4dB(A) at the same air flow.

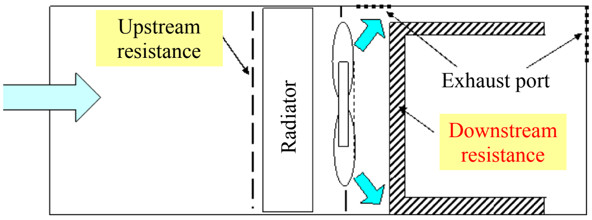

Fig. 19 Schematics of wind tunnel bench

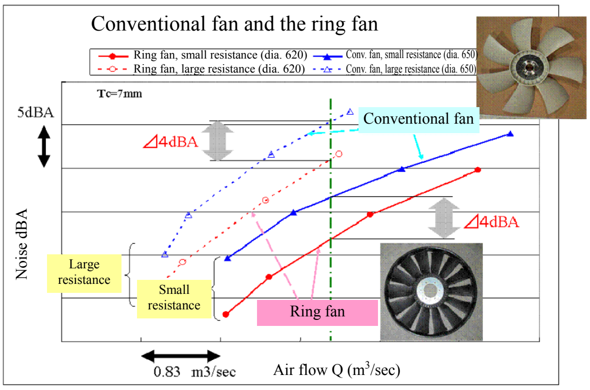

Fig. 20 Comparison of bench performances of conventional fan and the ring fan

Next, noise performances of a conventional fan and the ring fan equipped on a wheel loader and bulldozer are plotted in **Figs. 21** and **22**.

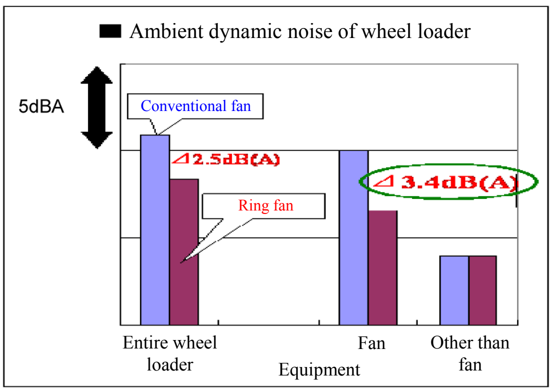

Fig. 21 Ambient dynamic noise of wheel loader

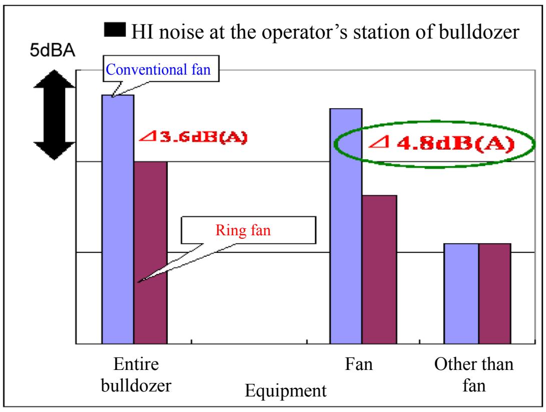

Fig. 22 HI operator ear noise of bulldozer

The results of actual machines do not correspond to the bench test results. This can be explained by the fact that impacts by parts around the fan are not taken into account in the bench tests and only noise and air flow of the fan itself (cooling assembly was installed) were measured. In the actual machines, a fan guard, hydraulic equipment, hoses, piping and other parts were installed as peripheral parts, which must have produced some impacts.

Results of a frequency analysis in actual machines are plotted in **Fig. 23**.
Not only fan NZ noise that was prominently reduced, but also broadband frequency noise were confirmed reduced.

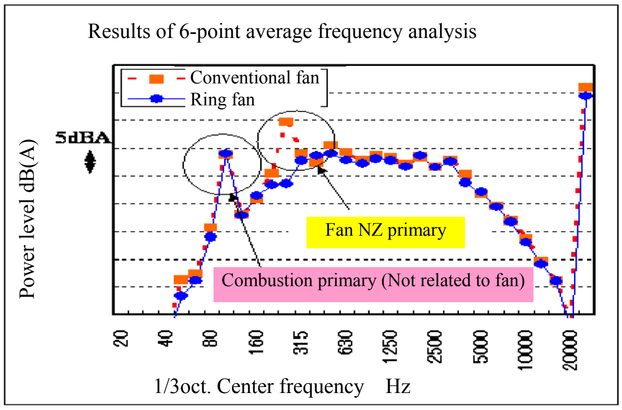

Fig. 23 Dynamic frequency analysis in actual machines

5. Future Plan

This development program was undertaken jointly with T.RAD Co., Ltd. (formerly Toyo Radiator Co., Ltd.). The development of the fan itself was mainly undertaken by T.RAD Co., while Komatsu mainly developed equipping of the fan including actual machine usage.

Our honest feeling is that a ring fan, which is already sold on the market, for use in construction machinery has finally and viably been developed after surmounting barriers such as low noise, restrictions peculiar to construction machinery, cost and strength, after studying how this ring fan can be adopted in construction machinery.

We plan to modify the fan shape to achieve a higher efficiency and to expand the product family to further utilize the technology gained so far.

References:

1) Chisachi Kato, et al., Tokyo University Production Research, Vol. 54, No. 1-2, Serial No. 624, pp66-70 (Jan. 2002).
2) Shimada, K., "Advanced Design of Radiator Cooling Fan for Automobiles," pp.79, 105 (2004).

Introduction of the writer

Haruhiro Tsubota

Entered Komatsu in 1979.
Currently assigned to Construction Equipment Innovation Center 2, Research Division.

[A few words from the writer]

In the past several years, my hobby has been swimming and I swim thinking how best I can swim a long distance easily, the angles of my hands when I throw them into water and what types of foams do I make around my hands while swimming the crawl.

How the balls of table tennis, golf and baseball behave and how flying disc stably moves are interesting to watch when we become aware of the existence of a fluid.

My conclusion is that a smooth flow of a fluid reduces eddies generated, producing efficient work with smaller losses.

The work related to a fluid and noise is difficult because fluids and noise are not visible. I feel everyday that work becomes very interesting by "visualizing" things.