Technical Paper

Development of Large Size Hybrid Fan

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A lot of small fans with three-dimensional, wide chord length, forward swept figure, and/or shroud ring have been developed and manufactured by injection molding. When we see large size fans, they are still two-dimensional old-fashioned steel fans. Therefore, a new series of hybrid fans (plastic blades + steel hub) was developed to meet the requirement of low noise and high efficiency. Key technologies of high performance hybrid fans are blade contours that generate gradual load change and the best compromise among noise, efficiency and strength.Using CFD and FEM, several blade contours are investigated varying curvature distribution and blade turning angles. As the results of the development, a lineup of hybrid fans up to diameter of 1450 mm has been completed.

Key words: *Hybrid Fan, Cooling Noise, Fan, Fan Noise*

1. Background

The most effective technology to meet the regulation of exhaust gas emission of diesel engine is Cooled EGR. However, if this technology is employed, heat rejection generally increases by 30% to 40%, requiring higher flow rate of fan. This is a serious problem for construction equipment that cannot get cooling air by traveling. As shown in **Figs. 1** and **2**, In EU and Japan, the regulation of dynamic noise of construction equipment is strengthened. On the other hand, the contribution of cooling noise in dynamic noise is very large, as shown in **Fig. 3**. As a measure for this problem, it is effective to minimize excess flow rate by controlling fan speed, as represented by hydraulic fan drive, but the demand for lowering the noise of fan itself is becoming stronger.

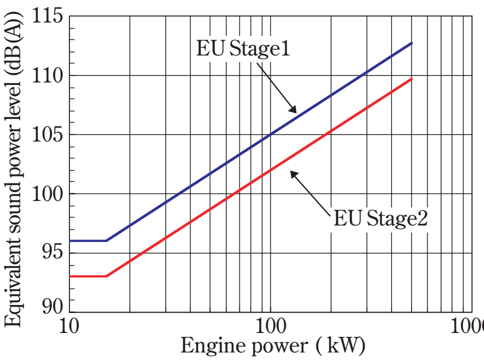

Fig. 1 Noise regulation of EU

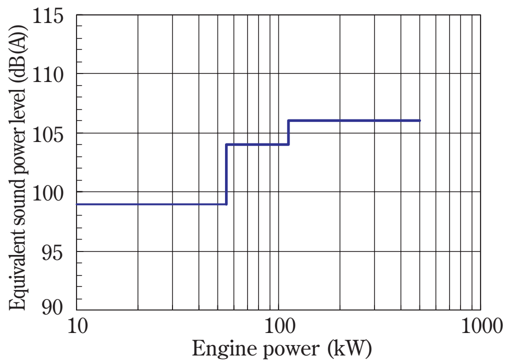

Fig. 2 Noise regulation in Japan

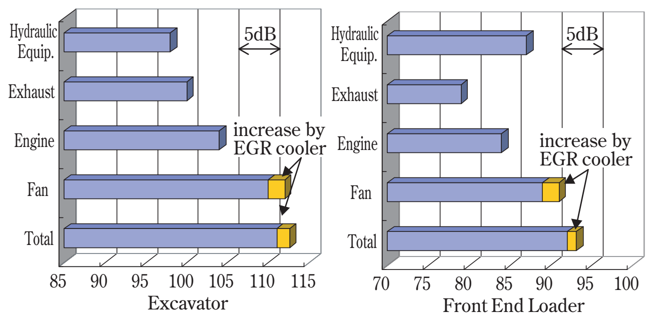

Fig. 3 Contribution to dynamic noise

2. Fan Series

Fig. 4 shows the series of Komatsu fans. 625 mm or smaller sizes are made of plastic, and 900 mm or larger sizes are all made of steel. Hybrid fan is manufactured in the range from 800 to 870 mm in size. The reason why large-size fans have been made of steel is that the manufacture of solid plastic fan requires precious injection molding mold and large-scale forming press, which is not suitable for small volume production, for example, of large-size models. Steel fan has the blades of uniform thickness, and it is impossible to change blade thickness along its length, so that blade chord length inevitably becomes short from the strength point of view. As a result, it has the following demerits:

(1) The solidity (blade chord length/pitch) at outer periphery is extremely short, which results in non-uniform flow between blades. (see **Fig. 5**)

(2) Because two-dimensional shape is generally used, if flow angle is matched on the outer diameter side, the incidence (attack angle) on the inner diameter side becomes large. (**Fig. 6**)

A means to solve these problems is hybrid fan. As is understood from its name, hybrid fan consists of plastic blades and steel hub (**Fig. 7**) and has the advantages of the both. It has the following advantages:

(1) Requires only one set of injection molding mold for one piece of blade, and can be formed with comparatively small press.

(2) Low stress because of the combination of high-strength hub and light-weight plastic blades, which enables the design of long chord blades

(3) Three-dimensional blade shape is possible although there is a slight limitation on design.

On the other hand, it has the following demerits:

(1) The joint between hub and blade tends to be discontinuous.

(2) The number of blades is limited because blades are jointed with hub by riveting.

Care must be taken to (1) because it not only obstructs flow but also causes stress concentration.

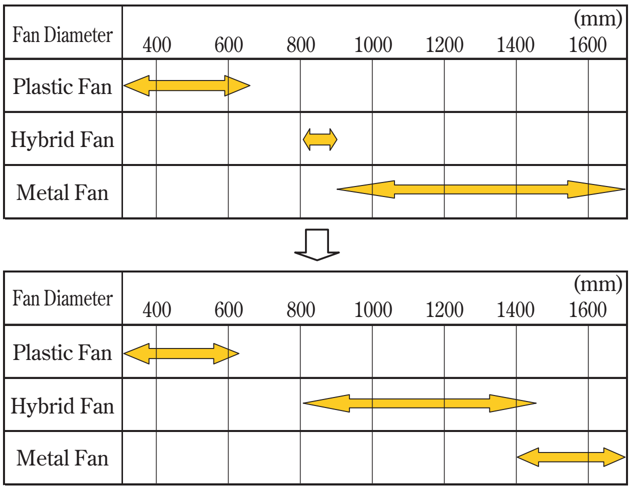

Fig. 4 Series of Komatsu fans

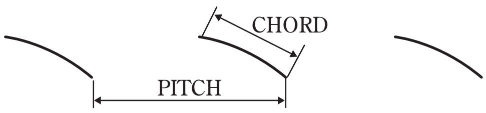

Fig. 5 Cylindrical cross-section of two-dimensional steel fan

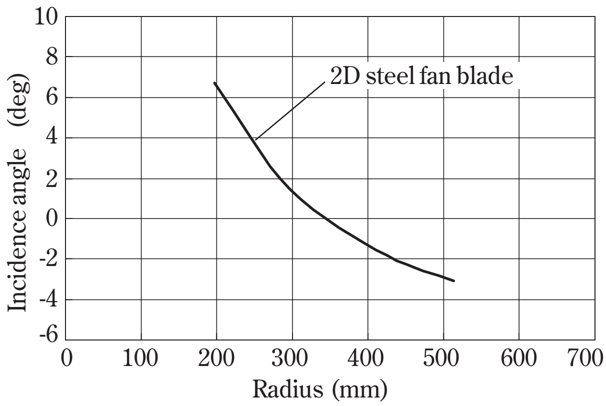

Fig. 6 Two-dimensional fan inlet incidence

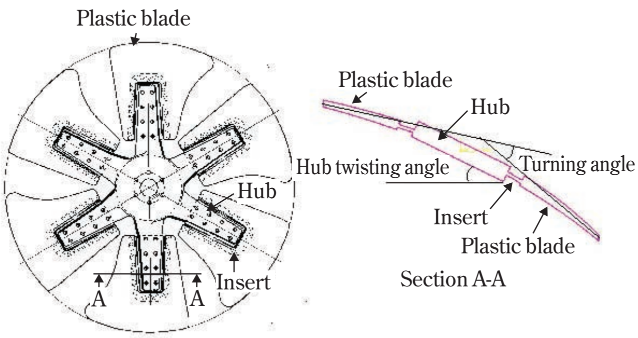

Fig. 7 Hybrid fan

3. Design Concept of Hybrid Fan

In general, fans for vehicle have small diameter ratio, compared with axial compressors or axial fans for gas turbine. As a result, the work and air flow rate that are used for pressure rise is smaller at the inner diameter portion where peripheral velocity is much lower than at the outer diameter portion. As shown in **Fig. 8**, flow velocity is reduced to a large extent at center portion even when disk portion is excluded. To obtain as uniform flow as possible, the hybrid fan of this time was designed under the following concept:

(1) Make turning angle larger toward inner diameter
(2) To improve solidity, make blade chord as long as strength permits, especially at outer diameter.
(3) Use forward swept-blades to restrict radial flow.

The (tested) samples of investigation are shown in **Table 1** and **Figs. 9** and **10**. They are all made up of 3 circular arcs and structured such that the stepping with hub is minimized. On the other hand, the blades of conventional steel fans and 850 mm class hybrid fans are made up of one circular arc. Type1 is the basic model. For Type2, the distribution of 3 circular arcs of Type1 is reversed. Types3 and 4 are the levels that are similar to Type1 in curvature distribution but differ only in turning angle. For the purpose of comparison, two-dimensional steel fan was also analyzed.

4. CFD Model

The software used for flow analysis is Star-CD, and calculation was performed for one blade, i.e. 1/6 model.

Element: Tetrahedron, hexahedron
Number of meshes: 300,000
Turbulence model: k – ε

Fig. 11 shows the mesh model. Shroud was made to be box type. Before starting this analysis, the comparison of calculation and experiment results was performed with the 850 mm hybrid fan to confirm a good coincidence. (**Fig. 12**)

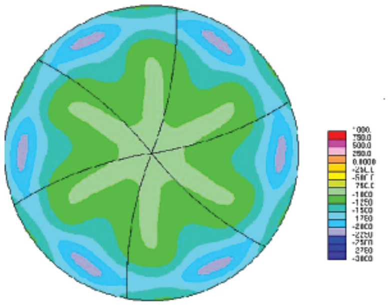

Fig. 8 Front face pressure distribution of steel fan

Table 1 Blade contour of investigated fans

	Diameter	Model	Description	Turning Angle	Curvature
Hybrid	1,120 mm	Type1	Base	31°	Inlet < Outlet
		Type2	Different Curvature	29°	Inlet > Outlet
		Type3	High Load	37°	Inlet < Outlet
		Type4	Light Load	27°	Inlet < Outlet
Metal	1,120 mm	–	Current Production	32°	Inlet = Outlet

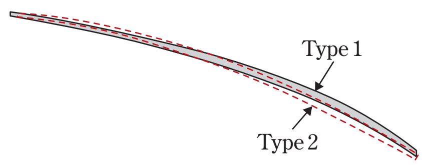

Fig. 9 Cross-section of Types1 and 2

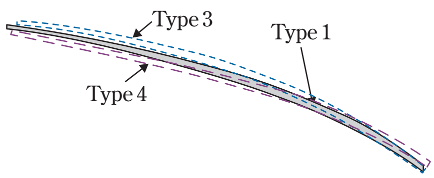

Fig. 10 Cross-section of Types3 and 4

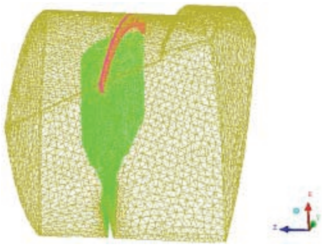

Fig. 11 Mesh used for calculation

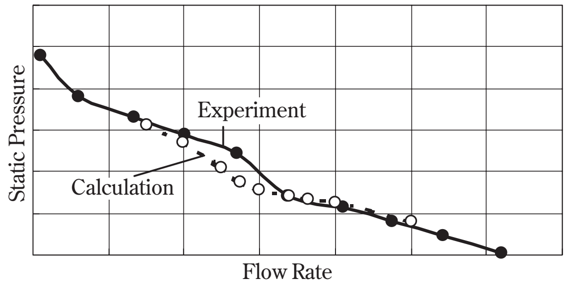

Fig. 12 Comparison with experiment (850 mm hybrid fan)

5. Result of Flow Analysis

Figs. 13 to **15** show the pressure distribution at 1080 mm diameter of steel fan, Type1 and Type2. Commonly for all investigated fans, on the pressure side, pressure gradually increases (flow velocity decreases) and then slightly decreases. No great difference was recognized though flow seems to have slightly worsened with the steel fan. On the other hand, on the suction side, pressure decreases at around inlet portion and then increases. Steel fan and Type2 showed a similar pattern, but Type1 shows an apparently different pattern. Because the conversion point of pressure (separation point of blade surface flow) is located more rearward on the blade, Type1 is most desirable.

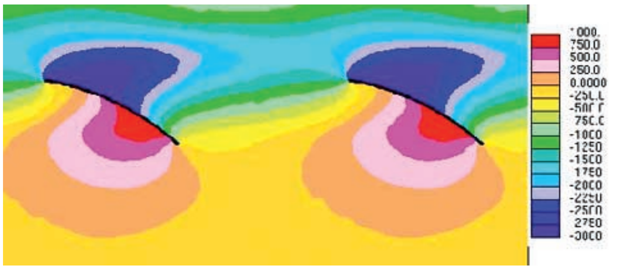

Fig. 13 Pressure distribution of two-dimensional fan (1080 mm)

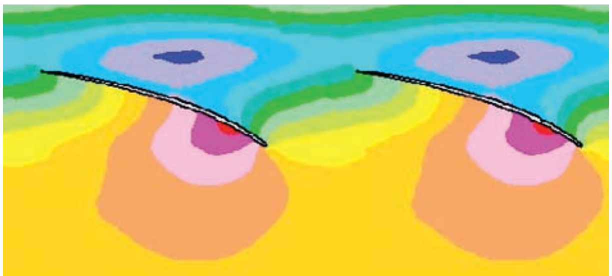

Fig. 14 Pressure distribution of Type1 (1080 mm)

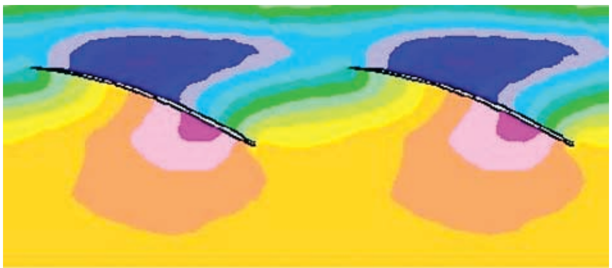

Fig. 15 Pressure distribution of Type2 (1080 mm)

Fig. 16 shows the comparison of blade surface flow between two-dimensional fan and Type1. It is clear that radial flow is restricted with Type1. **Figs. 17** and **18** show the flow at 1080 mm diameter of Types3 and 4 to see the influence of blade load (turning angle). Apparently Type4 has more desirable distribution, and the highest efficiency was achieved by this type4 (**Table 2**). Therefore, to design a high-efficiency fan, it is important to run the fan at allowable maximum speed and make the blade turning angle small. However, as described later, noise does not necessarily synchronize with efficiency, and low noise is achieved with higher blade load (greater blade turning angle) fan when pressure and air flow rate are the same. Therefore, optimization is necessary. This time, we selected Type1 as the best sample.

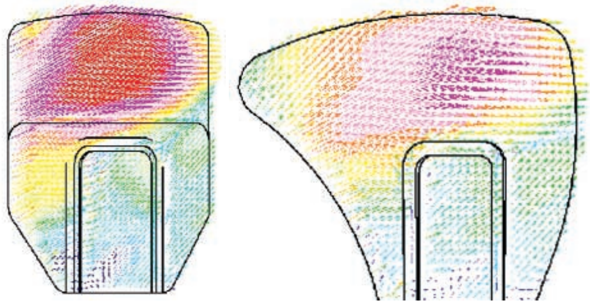

Fig. 16 Blade surface flow of two-dimensional and Type1 fans

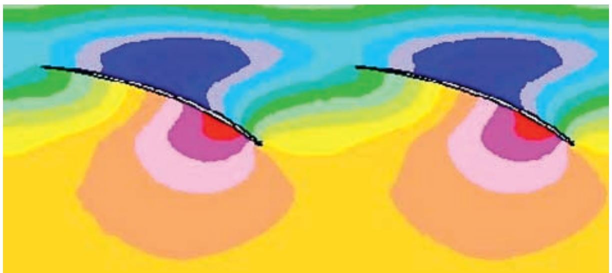

Fig. 17 Pressure distribution of Type3 (1080 mm)

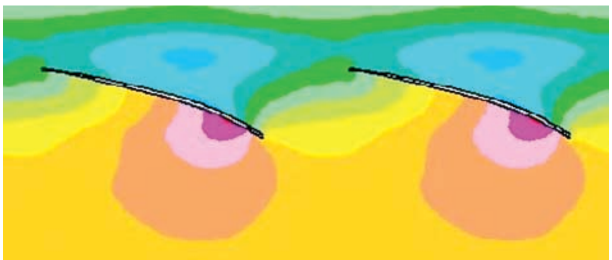

Fig. 18 Pressure distribution of Type4 (1080 mm)

Table 2 Result of performance prediction

	Model	Fan Speed	Efficiency
Hybrid	Type1	1,401 rpm	48%
	Type2	1,330 rpm	47%
	Type3	1,305 rpm	42%
	Type4	1,450 rpm	50%
Metal	–	1,317 rpm	42%

Figs. 19 and **20** show the pressure distribution at mean diameter (860 mm) and root of blade (560 mm) of Type1. A sharp pressure gradient, which seems to be the influence of incidence, is recognized at the tip of blade: on the pressure side for average diameter and on the suction side for root of blade. Similar phenomenon is recognized on the connecting surface with hub at root of blade. So, it seems that separation occurred. Concerning the front face pressure distribution shown in **Fig. 21**, though it is improved compared with steel fan shown in **Fig. 8**, the flow velocity at inner diameter is still low, compared with that at outer diameter. This seems to be the subject for future improvement.

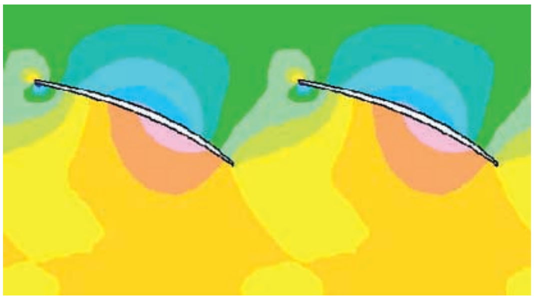

Fig. 19 Pressure distribution of Type1 (860 mm)

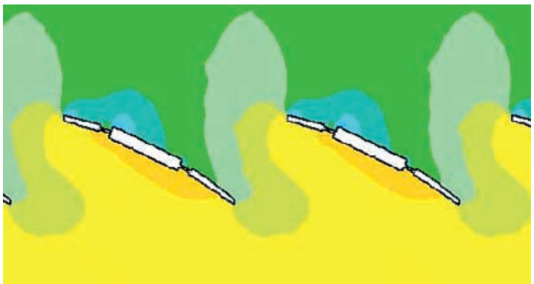

Fig. 20 Pressure distribution of Type1 (560 mm)

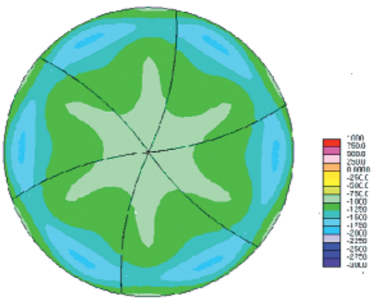

Fig. 21 Front face pressure distribution of Type1

6. Result of Performance and Noise Tests

Table 3 and **Fig. 22** compare the result of performance and noise tests between Type1 and steel fans. The air flow rate of Type1 is similar to that of steel fan, as predicted, but the difference of efficiency was not so great as simulated. Noise was reduced by approximately 3.4 dB. We also tested a blade whose twisting angle of hub was increased from 26° to 32°, aiming at obtaining the same effect as increasing the blade turning angle. As a result, with the fan having a large twisting angle, the speed to obtain the same flow rate could be reduced and noise level is also reduced though efficiency dropped. Therefore, in designing a fan, it is necessary to determine in advance to which of noise level and efficiency importance should be given.

Table 3 Result of performance and noise tests

Model	Hub Twisting Angle	Fan Speed	Efficiency	Noise
Hybrid	26°	1,342 rpm	46%	-3.4dB(A)
Type 1	32°	1,212 rpm	45%	-4.5dB(A)
Metal	26°	1,350 rpm	44%	–

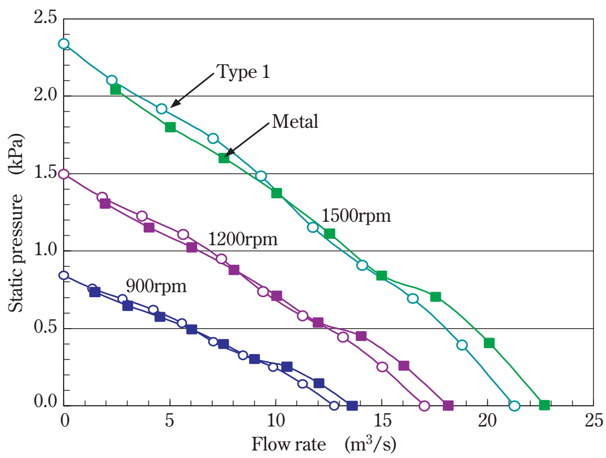

Fig. 22 Flow rate - pressure diagram

7. FEM Analysis

Because blade contour, especially blade chord length, is restricted by strength, flow analysis and stress analysis were performed simultaneously while feeding back the result to each other. **Fig. 23** shows the stress diagram due to centrifugal force. High stress occurred at the center of hub root portion and the corner of insert. The former can comparatively easily be corrected by using higher strength material or increasing the wall thickness of hub. The latter indicates that the stress is not simply tensile in radial direction and that bending stress occurs on the blade. This is because the blade element is not arranged in radial direction, and greatly influenced by blade chord length.

Concerning vibration mode, there occurred the first bending and torsional vibrations (**Fig. 24**). For fans, because they are combined with rectangular radiator, the resonance with 4th rotational vibration must be taken into consideration. For bending vibration, there is no problem even when it occurs in ordinary operation range. What must be avoided is the resonance with torsional vibration. Measures to be taken for this purpose include the optimization of blade thickness distribution and the increase of the area of steel part, such as hub and insert. However, if hub is extended, the surface of discontinuity increases and performance drops, as described before in flow analysis. On the other hand, insert can be formed in the same shape as blade, so that the probability of its becoming an obstruction to flow is comparatively low. Therefore, after the distribution of blade thickness was determined, we made effort to avoid torsional vibration by optimizing the shape of insert while limiting the extension of hub to the extent that there is little influence on efficiency. **Fig. 25** shows the final shape of insert. **Fig. 26** shows the contribution including the extension of hub.

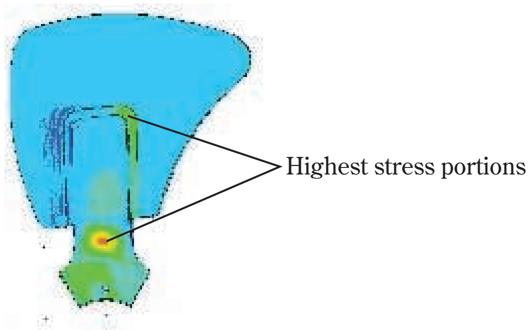

Fig. 23 Centrifugal stress distribution

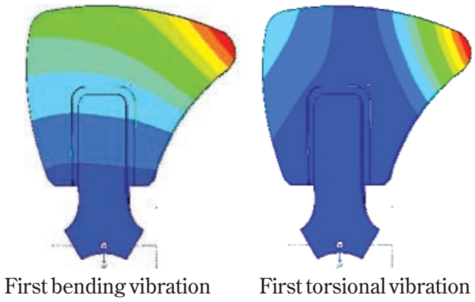

Fig. 24 Vibrational mode

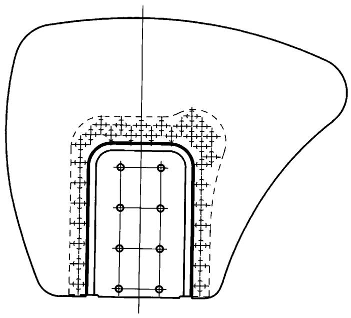

Fig. 25 Reinforced insert

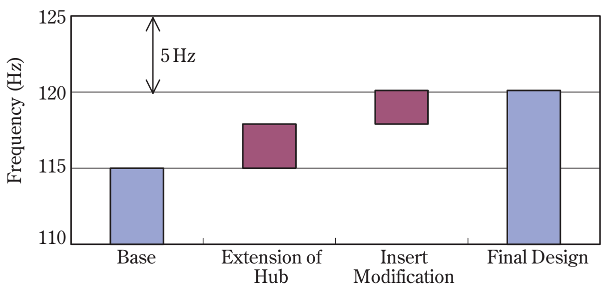

Fig. 26 Contribution to the increase of first torsional characteristic frequency

8. Result of Stress Measurement

Figs. 27 and **28** show the measurement result of average stress and vibrational stress under centrifugal force. The resonance with first torsional vibration and 4th rotational vibration is recognized around 1700 rpm, which agrees fairly well with our prediction. By way of precaution, we performed high-speed fatigue test to check reliability and durability.

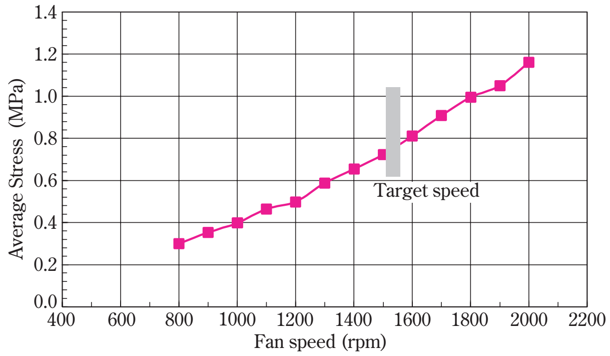

Fig. 27 Average stress (centrifugal stress)

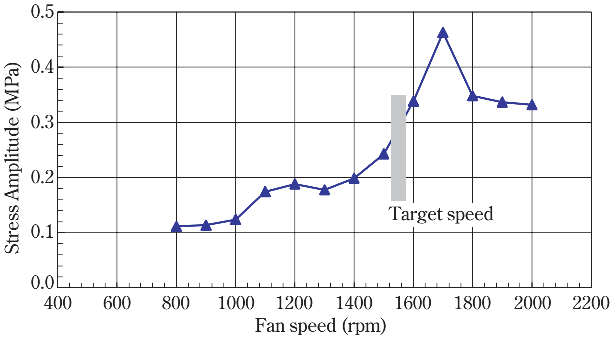

Fig. 28 Fluctuating stress (vibrational component)

9. Conclusion

(1) We developed a new large size hybrid fan with low noise and high efficiency and serialized it in the range from 850 mm to 1450 mm.

(2) The efficiency of fan is greatly influenced by its curvature distribution. To achieve high efficiency, it is important to make the portion of maximum curvature as rearward as possible and thus make flow separation delayed. Concerning blade load, it is advantageous for achieving high efficiency to make the blade turning angle small and run the fan at high peripheral velocity.

(3) Fan efficiency and the best value of noise do not necessarily coincide with each other and are sometimes in the relation of reciprocity. Therefore, in designing a fan, it is necessary to find an appropriate point of compromise between them.

(4) To increase the strength of fan, it is effective to match the shape of insert with that of blade and extend and widen the insert.

Introduction of the writers

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Entered Komatsu in 1969. Currently belongs to Industrial Power Alliance, Ltd.

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[A few words from writers]

It was the first opportunity for Komatsu to develop a fan by itself. Thanks to hearty cooperation of many departments, we could progress the development comparatively smoothly. Because the cost of jigs and molds is high, though not so high compared with full plastic fans, we rarely have a chance of development. We are grateful for being given such a good chance as this time development.