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A STUDY ON THE FRACTURE OF A SIROCCO FAN IMPELLER

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ABSTRACT - This paper describes numerical and experimental study on the fracture of the sirocco fan impeller applied in a window-type room air conditioner. The possibility of the fracture due to resonance as well as fatigue was investigated. To check the fracture due to fatigue, structural analysis was performed using the Finite Element Method. The safety factor based on von Mises failure criterion was induced to estimate the that of the sirocco fan. For the resonance, both modal experiment and flow analysis by Vortex Element Method was applied. The natural frequencies of those results were compared.

1. INTRODUCTION

A sirocco fan, a kind of centrifugal fan, has been widely applied to home and industrial appliances. It consists of rotating impellers, a scroll, a cut off, a bottom disk, a rim and an outlet duct as shown in Fig.1. The compartments of the impeller are blades, a rim, and a bottom disk. Owing to the mass balance, the flow around the sirocco fan inlet is entrained into the interior of sirocco fan, then most of the flow concentrate around rotating axis due to flow separation(Kind and Tobin, 1990) and go through the impeller. The static pressure increases along scroll surface. Finally the flow goes out the sirocco fan.

Because the air conditioner often turns on and off, the sirocco fan also repeats acceleration and deceleration. Owing to this operating condition, fracture due to periodic loading may be occurred. Since a sirocco fan usually has been made by engineering plastic, it is tend to deform and crack easily as comparing the metals. It is well known that the Young's modulus of plastic is lower than that of iron or aluminum, thus the natural frequency of plastic is lower than that of metals. Therefore there is a possibility to get damages due to the resonance, too. The reliability test was performed by 150 day's continuous operation at 824 RPM. We could find the cracks (see Fig. 2). From an examination, the crack was initiated near the junction where the rim fixes the blades and propagated to the blades and the disk. The crack was homogeneously distributed around the fan.

To check the possibility of the fracture due to the fatigue and resonance, both numerical and experimental approach was carried out. For the structural analysis, the commercial code ANSYS based on the Finite Element Method was employed. The estimation of the safety for the static loading and fatigue was performed using the failure criterion suggested by von Mises. The other possibility of the fracture is the resonance between the natural frequency of sirocco fan and characteristic frequency due to the aerodynamic forces. Experiment was carried out to see the natural frequency and numerical analysis based on the Vortex Element Method is performed to get the characteristic frequency. Comparing the natural frequencies that are calculated as described, we believe that resonance occurs.

2. COMPUTATIONAL METHODS

2.1 Structural Analysis

2.1.1 Governing Equation

To investigate the fracture of the sirocco fan, structural analysis was performed by F.E.M. based on the variational principles. Generally, the element stiffness matrix is formulated as (Zienkiewicz et al., 1989)

$$\overline{K}^e = \int_\Omega B^T D B d\Omega = \int_{-1}^{1}\int_{-1}^{1}\int_{-1}^{1} B^T D B |J| d\xi d\eta d\varsigma \tag{1}$$

where, **B** is a strain-displacement matrix, **D** is a material modulus matrix, and |J| is the determinants of Jacobian matrix. And Jacobian matrix, **J**, is described as

$$J = \begin{bmatrix} x_{,\xi} & x_{,\eta} & x_{,\varsigma} \\ y_{,\xi} & y_{,\eta} & y_{,\varsigma} \\ z_{,\xi} & z_{,\eta} & z_{,\varsigma} \end{bmatrix} \tag{2}$$

To transform the element stiffness matrix into the global stiffness matrix, coordinate transformation matrix $\mathbf{T^e}$ is used as

$$K^e = T^e \overline{K}^e T^{eT} \tag{3}$$

After assembling the global stiffness matrix, we obtain the equilibrium equation with the nodal displacement vector δ and nodal force vector **F** as

$$K\delta = F \tag{4}$$

where, $K = \sum_{a=1}^{Nel} K_a^e, F = \sum_{a=1}^{Nel} \bar{f}_a^e$.

2.1.2 Failure Criterion

Under the multi-axial loading conditions, failure criterion is an assumption as to the limitation of elastic deformation in a material. It can be decided whether the plastic deformation is occurred or not.

Based on the shearing strain energy theory, failure is occurred if shear deformation energy reaches a critical value, von Mises proposed the failure criterion as bellow.(Kim, 1991) The equivalent stress, ($\bar{\sigma}$) is defined as

$$\bar{\sigma} = \sqrt{\frac{1}{2}\{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\}} \tag{5}$$

where, $\sigma_1, \sigma_2, \sigma_3$ are principal stresses. And it is assumed that if equivalent stress is reached the axial yield stress Y, then the material begins failure. It is convenient to define the strength ratio (κ) as a failure index as

$$\bar{\sigma} = \kappa Y \tag{6}$$

The estimation of the strength ratio can be accomplished as follows; i) κ=0, no loading is applied. ii) κ<1, the structure is safe under this loading. iii) κ=1, the structure is about to fail. iv) κ>1, the structure has been failed. Also, strength ratio is a quantitative index to present the failure. If κ=0.5, then we can regard safety factor as 2.

2.2 Flow Analysis

The flow pattern of the sirocco fan is basically 3 dimensional and very complex and it is difficult to calculate fully three-dimensional flow due to the rotating blades and the complexity of the geometry. However we are interested only in the frequency characteristics of the aerodynamic force. Since transient computation takes so much time and the purpose of this calculation is to obtain the frequency characteristic of the aerodynamic force on the blades, the calculation in this study was done with 2 dimensional flow assumption.

2.2.1 Governing Equation

In an inviscid and incompressible flow, the governing equation of the flow can be describe by the velocity potential, ϕ, satisfying Laplace equation.

$$\nabla^2\phi = 0, \vec{u} = \nabla\phi \tag{7}$$

where $\vec{u}$ is velocity vector. Since the normal component of the relative velocity to a boundary surface is zero, we have the following relationship.

$$\vec{n} \cdot (\vec{u} - \vec{u_B}) = 0 \tag{8}$$

where, $\vec{u_B}$ is the velocity on the boundary surface. In the infinite boundary surface, the disturbance of velocity field due to object is zero.

$$\lim_{r\to\infty} \vec{u} = 0 \tag{9}$$

Applying the curl to Navier-Stokes equation, two dimensional incompressible vorticity transport equation is obtained as following;

$$\frac{\partial \omega}{\partial t} + \vec{u} \cdot \nabla \omega = \upsilon \nabla^2 \omega \tag{10}$$

To solve the Eq. (10), it is convenient to divide two step and calculate the solution at each step(Chorin, 1973).

$$\frac{\partial \omega}{\partial t} + \vec{u} \cdot \nabla \omega = 0 \tag{11}$$

$$\frac{\partial \omega}{\partial t} = \upsilon \nabla^2 \omega \tag{12}$$

The first step in Eq. (11), it means to transport the vortex due to convection and the vortex is transported in order to satisfy the solution of Eq. (11). In Eq. (11), the solution about vorticit, ω, is

$$\vec{u}(\vec{x}) = \int \vec{K}_\delta(\vec{x} - \vec{x}')\omega(\vec{x}')d\vec{x}' = \sum_{i=1}^{N} \Gamma_i \vec{K}_\delta(\vec{x} - \vec{x}_i) \tag{13}$$

where, N is the number of vortex in the flow field, and $\vec{K}_\delta(\vec{x})$ integral kernel of Poisson equation. In Eq. (12), it presents the transportation of the vortex due to diffusion and it simulates statistically through random walk method. In this study, it is so small that the diffusion term due to viscosity is negligible because a sirocco fan has high Reynolds number.

2.2.2 Flow Analysis in a Sirocco Fan

To calculate the flow including rotating blades in the calculation domain, the blade surfaces were discretized into elements, the vortices were distributed, and the strength of vortices was calculated to satisfy the boundary condition. In connection with the several blades, a multiply connected problem is established. Under the assumption that each blade effects each other with a linear relation, the matrix for the rotating blades is obtained by Eq.(14).

$$\begin{bmatrix} K^{1,1} & K^{1,2} & \cdots & K^{1,Q-1} & K^{1,Q} \\ K^{2,1} & K^{2,2} & \cdots & K^{2,Q-1} & K^{2,Q} \\ \vdots & \vdots & & \vdots & \vdots \\ K^{Q,1} & K^{Q,2} & \cdots & K^{Q,Q-1} & K^{Q,Q} \end{bmatrix} \begin{pmatrix} \Gamma^1 \\ \Gamma^2 \\ \vdots \\ \Gamma^Q \end{pmatrix} = \begin{pmatrix} rhs^1 \\ rhs^2 \\ \vdots \\ rhs^Q \end{pmatrix} \tag{14}$$

where Q means blade number, superscript vortex group at each blade, and $K^{i,j}$ the effects of vortex group in the j-th blade versus i-th vortex group. The discrete source method was used here and a point source was used for an inlet and an outlet condition. That condition reflects that the flow is constant from center to blade inlet direction. For the boundary condition in rotating blade surfaces, Equation (15) was applied.

$$\left[\left(\vec{u}_{bv} + \vec{u}_{wv} + \vec{u}_{bs} \right) - \vec{\Omega} \times \vec{r} \right] \cdot \vec{n} = 0 \tag{15}$$

where, $\vec{u}_{bv}$ is velocity due to vortex on the blade, $\vec{u}_{wv}$ velocity due to shedding vortex, $\vec{u}_{bs}$ velocity due to source term, $\vec{r}$ position of collocation point, $\vec{\Omega}$, angular velocity of blade, $\vec{n}$ unit vector in the normal direction. It should be noted that it is necessary to decide the position of shedding vortex. Because the flow direction of each blade is different, the position of shedding vortex must be placed in trailing edge of each blade.

3. RESULTS AND DISCUSSIONS

3.1 Fatigue

As mentioned before, one of the reasons to crack is fatigue. To investigate the safety factor against the fatigue, static analysis is pre-calculated. From the contour plot of strength ratio under the static loading was displayed in Fig. 3. The safety factor can be obtained by a reciprocal of the strength ratio. As shown in Fig. 3, the stress is concentrated around the rim due to the centrifugal force and the torsion resulted from the aerodynamic force. It should be noted that the centrifugal force is proportional to $r\omega^2$. However the safety factor is about 37. Therefore the rotating impeller is safe against the static loading. The second possibility of the fracture is the fatigue. It is generally believed that the structure having the safety factor 10~15 under the static loading is safe under the fatigue (Park, 1981). Since the safety factor in this case is about 37, the impeller of the sirocco fan seems to be safe against the fatigue.

3.2 Resonance

The remaining possibility of the impeller fracture is the resonance between the natural frequency of sirocco fan and characteristic frequency due to the aerodynamic forces. The experiment was done with an impact hammer, an accelerometer, and the FFT analyzer (B&K) as shown in Fig. 4. The sampling rate was 0.00125 sec. Because of the periodic impeller geometry, the frequencies of the first and second modes were 36 Hz, 36 Hz. And those of the third and fourth mode were 62 Hz, 62 Hz (see Fig. 5). Using the Vortex Element Method, the power spectrum of the lift force was evaluated to find the dominant frequencies, which may affect on the impeller crack. Discernible peaks were found as shown in Fig. 6 and the peak frequencies were 12.1, 24.5, 36.6, 49.1, and 61.1 Hz, respectively. It should be noted that the magnitude of third and fifth peak is very large. The amplitude at high frequency is small as shown in Fig.4. It must be noted that the frequency of the third mode by experiment corresponds to the fifth frequency of the aerodynamic force. Thus, it occurred the resonance and resulted in the crack of the impeller.

4. CONCLUDING REMARKS

To investigate the failure of the sirocco fan applied in a window-type air conditioner, numerical and experimental approaches were carried out. The structural analysis showed that the stress is concentrated around the rim due to the centrifugal force and the torsion resulted from the aerodynamic force. Estimation based on strength ratio indicated that the failure did not result from the fatigue. The Vortex Element Method is applied to see the characteristic frequency under the aerodynamic force. The power spectrum of the aerodynamic force was evaluated. The several peak frequencies were observed due to the asymmetric scroll shape as shown in Fig. 6. The fifth frequency of the aerodynamic force is nearly equal to the third natural frequency by experiment. Therefore we believe that the resonance in this sirocco fan impeller is the reason for the impeller crack.

REFERENCES

Chorin, A.J., 1973, "Numerical Study of Slightly Viscous Flow," J. Fluid Mech., Vol. 57, pp.785-796

Kim, D. H., 1991, Plasticity, Chung-Mun Gag (in Korea)

Kind, R.J. and Tobin, M.G., 1990, "Flow in a Centrifugal Fan and the Squirrel-Cage Fan Noise," TRANS. ASME J. of Turbomachinery, Vol. 112, pp.84~90

Park Young Jo, 1981, Machine design, Bo-Sung Munwha-Sa (in Korea)

Zienkiewicz & R.L. Taylor, 1989, "The Finite Element Method", 4th Ed., Vol. 1.

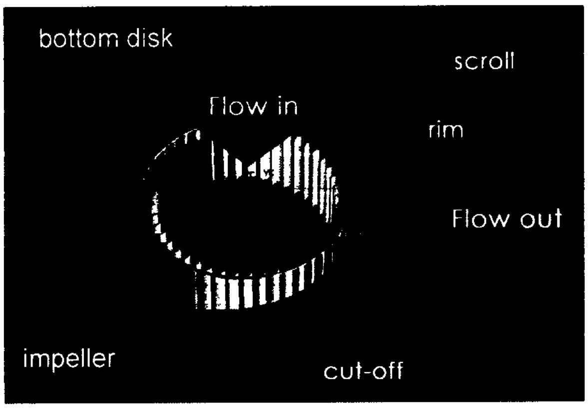

Fig. 1 Schematic Diagram Of A Sirocco Fan

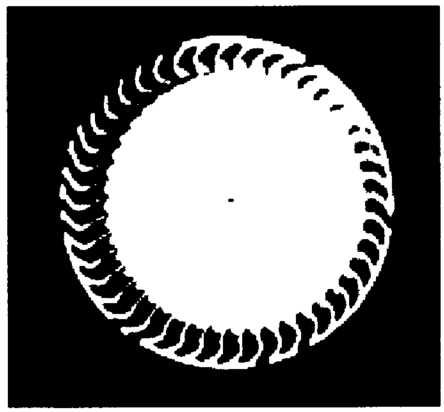

Fig. 2 Cracked Impeller

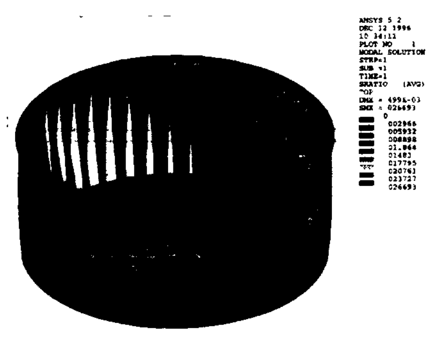

Fig. 3 Strength Ratio Contour Plot

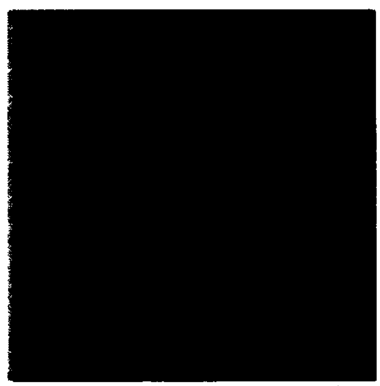

Fig. 4 Experiment Equipment

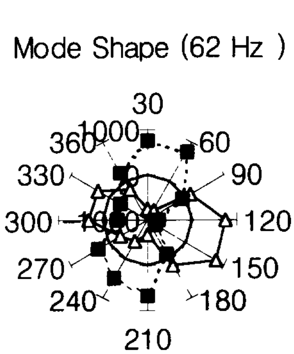

Fig. 5 Mode Shape at 62 Hz

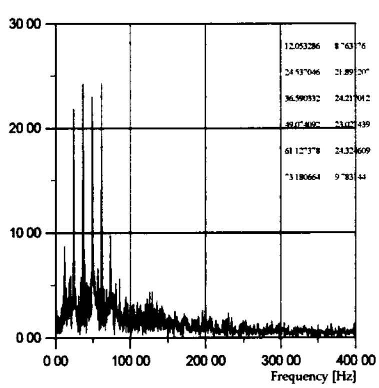

Fig. 6 Power Spectrum of the Aerodynamic Force