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Study on Blade Forced Vibration Response of Radial Inflow Turbine

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ABSTRACT

In the turbo machinery, predicting the vibratory response of the blade is one of the important items of the structural integrity. In this paper, simplified method utilizing the steady flow analysis was proposed for this purpose. This method was applied to predict the blade vibratory response of the radial turbine impeller against the excitation caused by scroll tongue. At first, this simplified method was compared with the method based on unsteady flow analysis to examine the validity and limitation. After that, this method was applied to predict the effect of scroll shape and operation on the blade vibration response. Some findings are obtained and comparison with experimental result shows the validity of this method for predicting the tendency, though some technical problems should be solved to achieve more correct quantitative prediction.

NOMENCLATURE

FH	scroll inlet throat area
FI	impeller exit throat area
Pvt	turbine inlet pressure
ΔP	pressure difference of pressure surface and suction surface of the blade
$\Delta\sigma$	resonant stress at max stress location
ϕ	azimuth angle of scroll

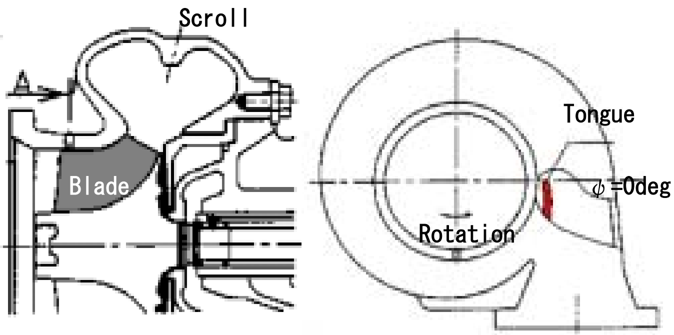
INTRODUCTION

It is an important subject to predict the forced vibration level of turbo machinery blade. Though there are many types of excitation source, spatial un-uniformity of flow condition is one of the main causes of blade forced vibration. When we think about a turbine component which consists of rotating impeller and stationary parts such as scroll located ahead of impellor, flow from the stationary parts is not uniform but has a certain amount of distribution. Under the influence of this distribution, the surface pressure of the specific blade is fluctuated time after time while the impeller rotates. This pressure fluctuation causes the excessive vibratory response if the resonant (the condition in which fluctuation frequency coincides with the blade natural frequency) occurs. This pressure fluctuation works as an excitation power to the blade and the resonant stress is very much dependent to this as much as structural damping. For this reason, it is required to understand the flow field and to predict the pressure fluctuation on blade surface caused by the circumferential distribution of flow condition.

To predict this pressure fluctuation with sufficient accuracy, it is desirable to perform unsteady flow analysis. It is technically possible since calculation technology and hardware are progressing now. However, it is still not effective to apply this to an actual design routine from the reason of a period, an expense, and additionally a handling of this kind of analysis. Therefore, the simplification based on a certain assumption is required to use as a design tool. In axial turbine, because the flow can be generally assumed to be inviscid, inviscid unsteady flow analysis is performed, and is used as a design tool (Hsiao-Wei et al., 1992), (Kato et al., 1999). Contrarily, in radial turbine flow, assumption of inviscid flow is not appropriate even in the case of steady flow since the influence of a three-dimensional flow is strong compared with an axial turbine, and viscous steady flow analysis is widely used for the blade design of a radial turbine. Considering this situation, the simplified method based on many viscous steady flow analyses was proposed to predict blade surface pressure fluctuation, and resonant stress of radial turbine impeller was predicted utilizing this pressure fluctuation as an excitation force.

ANALYSIS METHOD

A shape of a radial turbine is shown in Fig.1. A radial turbine consists of a scroll located ahead and a rotating impeller blade that is located in the back. The flow disarrangement caused by a tongue of scroll brings about blade vibration.



(a) Cross section (b) View from A

Fig. 1 Radial inflow turbine

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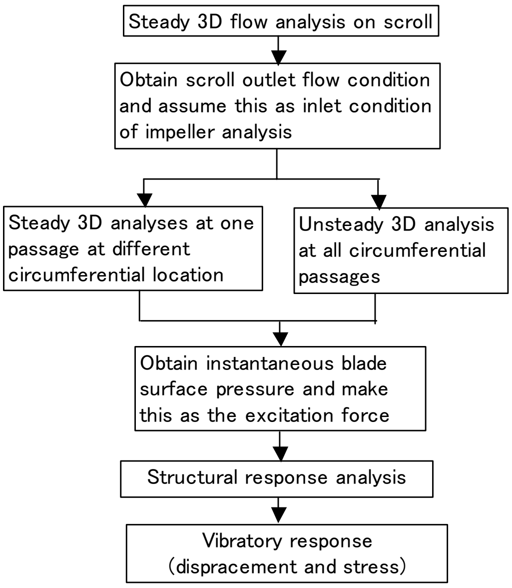
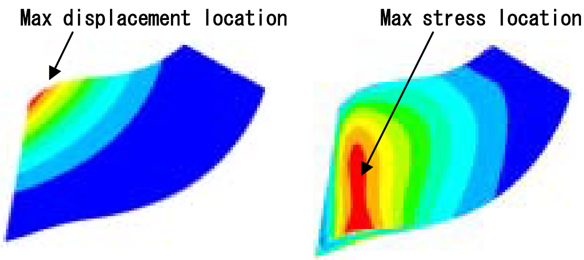


Fig. 2 Blade resonant stress prediction flow



(a) Displacement contour (b) Stress contour

Fig. 3 Structural eigenvalue analysis result

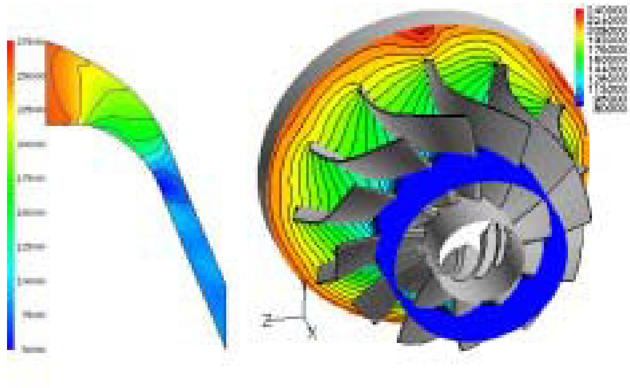
The flow chart for predicting blade resonant stress is shown in Fig.2. Flow analysis of the scroll is performed at first and the scroll outlet flow distribution is obtained. This distribution is assumed as the inlet condition of the impeller cascade blade flow analysis and blade surface pressure change is obtained by steady or unsteady cascade flow analysis. This pressure fluctuation is then decomposed to each excitation order by performing Fourier series decomposition and the vibratory displacement of the blade can be calculated by frequency response analysis by making the surface pressure pattern as an external force for the object excitation order. At the end, the computed displacement is converted into stress. High vibratory stress by resonance between the first mode natural frequency of the blade and the fifth excitation order (5EO) of revolution was measured by experiment, and we selected this resonance as a main object of vibratory stress evaluation. Displacement and stress distribution of the object mode obtained from the structural eigenvalue analysis is shown in Fig.3. In this response analysis, modal damping of 0.0015 (in damping ratio) was used from the experimental measurement.

The detail of the impeller flow analysis is as follows. When the simplified method based on steady flow analysis is chosen, the blade inlet conditions for every time step are computed from the scroll analysis result because the relative position of the blade and the scroll changes as the impeller rotates. Each blade surface pressure is computed by performing steady analysis at one blade passage for this every time step. This calculation code is three-dimensional viscous analysis widely used for the blade design of a radial turbine. This analysis result is assumed as the pressure fluctuation of blade surface while the blade goes around scroll. In actual flow, it takes time for the fluid to arrive from leading edge to trailing edge of the blade. In this simplified method, unsteady effect of the flow cannot be taken into account. On the other hand, the method using unsteady flow analysis can predict more precise flow field. When the method based on unsteady flow analysis is chosen, all circumferential passages are calculated at one time by unsteady three-dimensional viscous analysis. For this case, unsteady effect can be taken into account though it takes much time to calculate. The results of these two methods were compared, and the propriety of the simplified method was evaluated.

ANALYSIS RESULTS

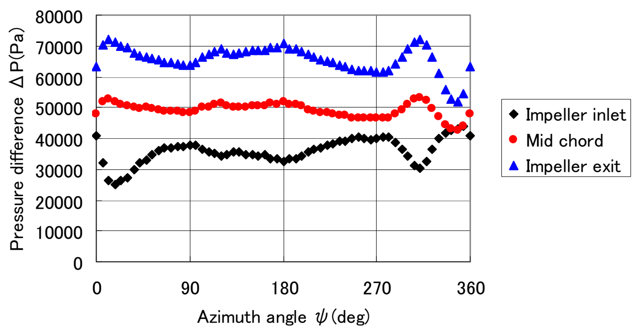
Comparison of Steady and Unsteady Flow Analysis

The result of the blade flow analysis is shown in Fig.4. In the case of steady analysis, many steady analyses at one passage were performed changing inlet condition. In the case of unsteady flow analysis, the all circumferential passages of the blades were calculated at one time.

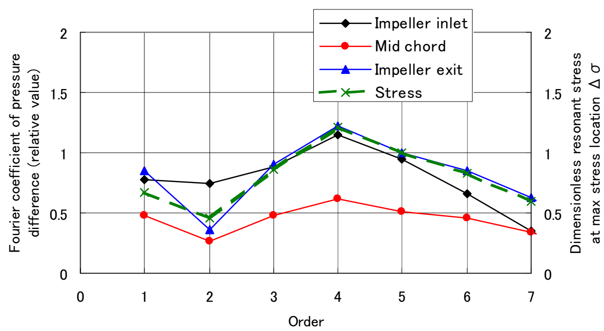


(a) Steady analysis at one passage (b) Unsteady analysis at all circumferential passages

Fig. 4 Impeller analysis result (static pressure)

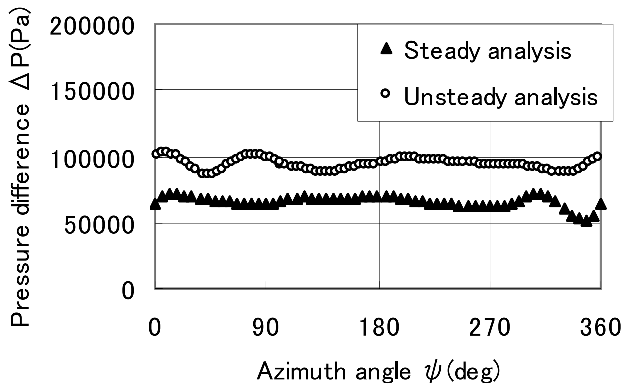


(a) Blade surface pressure difference at tip side

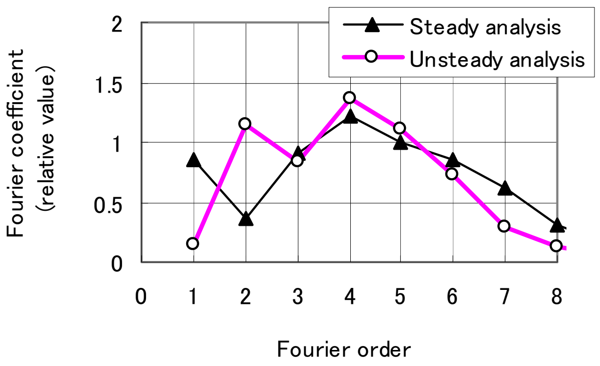


(b) Fourier analysis result and resonant stress

Fig. 5 Calculation result of impeller CFD analysis and resonant stress on each order excitation response



(a) Blade surface pressure difference at exit of tip side



(b) Fourier analysis result of (a)

Fig. 6 Calculation result of impeller CFD analysis

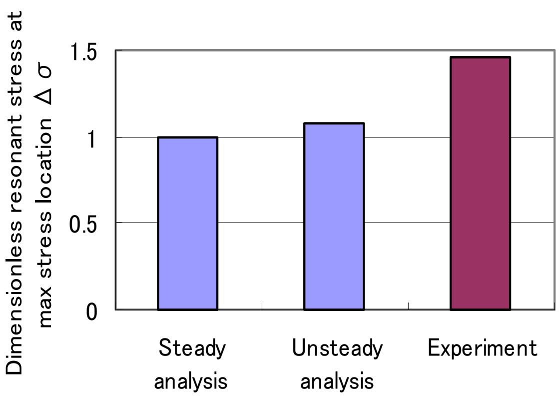
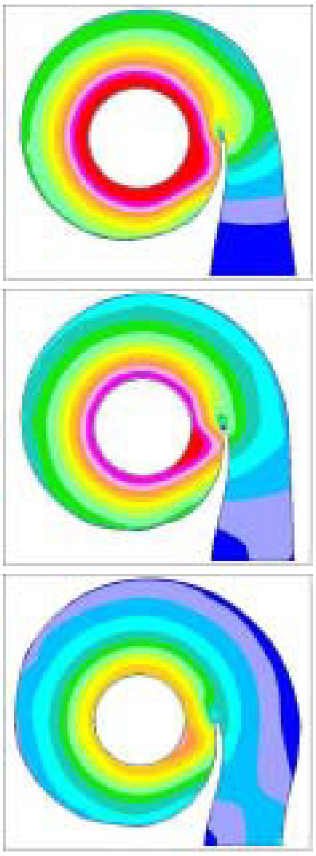


Fig.7 Comparison of predicted and field experience on 5th excitation order response

The bending force for blade is caused by the pressure difference between both (pressure and suction) surface of the blade, and the total effective vibratory force for this mode is mostly affected by that of exit of tip region as shown in Fig.5. For this reason, fluctuation of pressure difference (ΔP) at this point (90%chord, 90%span) is specifically shown in Fig.6. The distribution of steady analysis is similar to that of unsteady analysis, though the phase and the value are different. The phase is delayed in the case of unsteady analysis, because it takes time for the fluid to arrive from leading edge to trailing edge of the blade. ΔP of steady analysis is lower than that of unsteady analysis. This is considered because the steady analysis mesh has a cusp at trailing edge for the stability of calculation and blade thickness in this area is thinner than the actual dimension, while the mesh has no cusp in unsteady analysis. The tendencies of Fourier coefficient are alike in both (steady and unsteady) analyses for third or higher order component. Though some difference which may be caused by the unsteady effect is appeared in first or second order component, this may not affect on the vibratory response as the blade resonance is caused by fifth excitation order response. As shown in Fig.7, the stress calculated by steady analysis is similar to the stress of unsteady analysis. So the simplified method based on steady analysis is proper for predicting the blade surface pressure fluctuation. But the calculated stress is smaller than the stress of experimental result. This reason is considered as the problem of the vibration analysis model and the reliability of damping. In this vibration analysis, structural model was only the blade portion, and disk portion was not included in this model. And few damping data of this blade are obtained. So it is needed to solve these problems in future.

Study about Influence of Turbine Volume

After confirming the validity and limitation of this method, we tried to apply this method to predict the effect of scroll shape on the blade fifth order excitation vibration response. According to the design curve previously obtained by experiment, the resonant stress becomes small when the value of FH/FI (scroll inlet throat area / impeller exit throat area) becomes large. We applied this method to examine whether this simplified method could predict this tendency or not. To achieve different values of FH/FI, three types of scroll which have different values of FH were selected for the same impeller. Fig.8 shows the flow calculation result for these three types of scroll. The flow rate of large scroll is larger than that of small scroll. But the Mach number at the scroll exit is small because the pressure drop is small in the large scroll. These calculation results were used for impeller analysis and the pressure distribution on blade surface was obtained. The fluctuation of ΔP at blade exit of tip side is shown in Fig.9 with their Fourier analysis results. In large scroll, the change of ΔP is flat and no significant fluctuation is appeared in Fig.9(a). Relating to this, the value of Fourier coefficient is small over the all order components in Fig. 9(b). The relation between turbine volume and the calculated resonant stress for the fifth order excitation is shown in Fig.11. This calculation method could predict the tendency of volume and stress, though the value was smaller than the value from experiment. The difference between experiment and calculation is larger in the case of large scroll volume than small and middle cases. The reason is thought that in the case of large scroll volume, the accuracy of the experiment or the calculation is not enough, because the resonant stress is small. Resonant vibratory stress up to seventh order excitation were also obtained and shown in Fig.10. Through this resonance is the virtual one (the flow condition dose not matched to the rotational speed of each resonance) except the fifth order resonance as described before, it is interesting that the tendency of each order component of resonant stress is very similar to that of Fig.9 (b). The strong correlation of resonant stress with the fluctuation of ΔP at blade exit of tip side was also supposed from this fact.



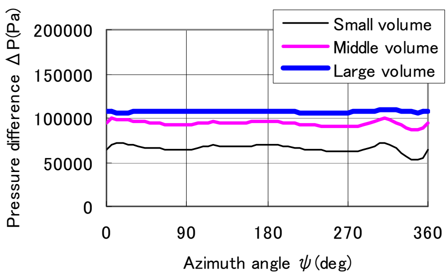
(a) Scroll of small volume
FH=1.0*

(b) Scroll of middle volume
FH=1.4*

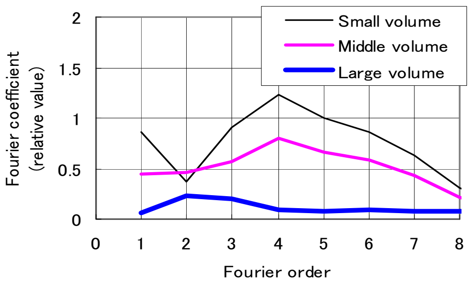
(c) Scroll of large volume
FH=2.3*

(*: relative value)

Fig. 8 Scroll CFD result (Mach number contour)



(a) Blade surface pressure difference



(b) Fourier analysis result of (a)

Fig. 9 Calculation result of impeller CFD analysis

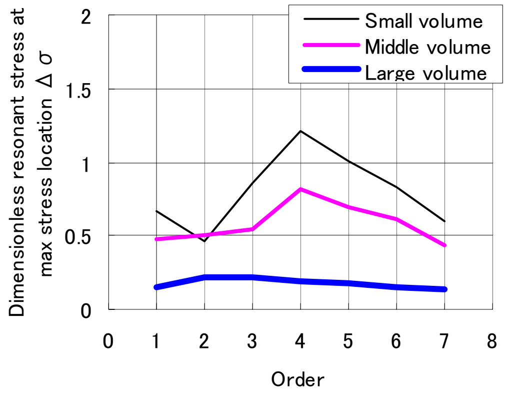


Fig. 10 Resonant stress by calculation on each order excitation response

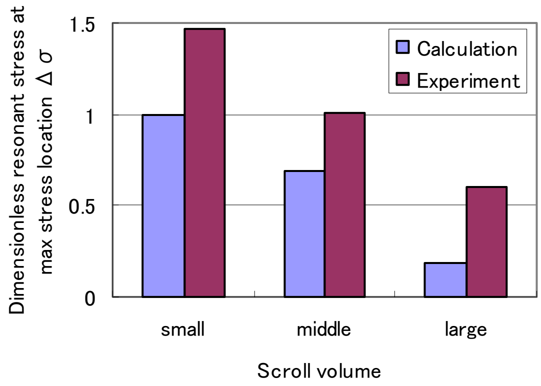


Fig. 11 Comparison of predicted and field experience on 5th excitation order response

Study about Influence of Turbine Inlet Pressure

In the next step, this simplified method was also utilized to study about the relation of turbine inlet pressure and resonant stress. The calculations were performed at three different turbine inlet pressure conditions for the same (small volume) scroll and the same rotating speed. The calculation result is shown in Fig.12. As shown in Fig.12, the stress increases in proportion to the turbine inlet pressure. This tendency agrees with the experimental result.

From the study about the scroll volume and about the turbine inlet pressure, we found that the resonant stress became larger either when the scroll throat area became smaller, or when turbine inlet pressure became higher. According to this fact and reminding that the scroll exit flow speed becomes higher either when the scroll throat area becomes smaller, or when turbine inlet pressure becomes higher, calculated resonant stresses in Fig.11 and Fig.12 are re-plotted in the manner of scroll exit Mach number and are shown in Fig.13. As shown in Fig.13, resonant stresses obtained by the scroll volume study and that obtained by turbine inlet pressure study all fall into the same curve. The reason why the resonant stress can be arranged by the flow speed of the scroll exit is considered because the excitation power to the blade depends on the change of flow angle and that of flow speed, and furthermore, because the change of flow angle is kept almost constant in this study as all scroll has the same tongue configuration. The situation of scroll design modification with impeller and tongue configuration unchanged is well happened in actual design and the findings obtained above should be effective for predicting the resonant stress of the blade in such a situation.

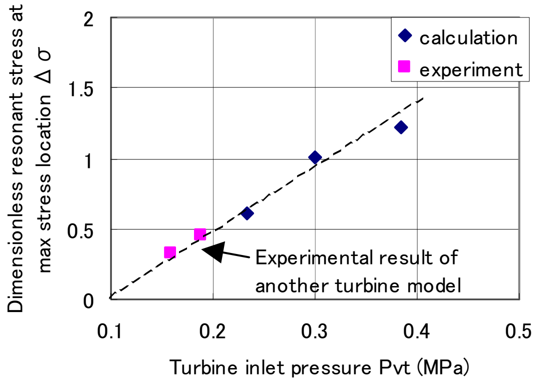


Fig. 12 Relation of turbine inlet pressure to resonant stress

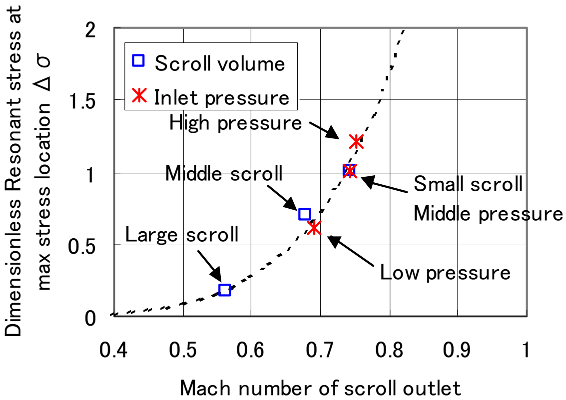


Fig. 13 Relation between Mach number of scroll exit and resonant stress by calculation

CONCLUSION

A simplified method based on steady flow analysis was proposed to predict resonant stress on a radial turbine impeller. Many steady flow analyses of the blade were performed to predict the pressure change on blade surface. This simplified method was compared with the method based on unsteady flow analysis, and it was confirmed that this simplified method was proper for predicting resonant stress. In the next step, this method was applied to predict a tendency of change of resonant stress when the scroll volume and turbine inlet pressure were changed. The result showed the validity of this method, and the effective finding for actual scroll modification that the resonant stress could be arranged by the flow speed of the scroll exit was obtained.

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