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Damage Informatics for Steam Turbine Components

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I. Introduction

Fossil power plants still play important roles for providing electric power supply on demands all over the world. Although combined cycle plants coupling gas turbines and steam turbines have become more popular due to their higher efficiency, the conventional steam turbine plants still occupy the large part of power stations and have become aged by long term service, requiring cost-effective maintenance application. To make optimum maintenance planning, risk-based maintenance[1]-[5] procedures have been established and applied to actual plants but the objective parts have been restricted and comprehensive evaluations of turbine major sections have been required. However the systematic lists of events to be considered have not been provided according to the wide variety of events and the lack of rational scenario making procedures. The fundamentals of manipulating damage information are statistical data processing and causality inference [6] from the observed event items but the latter term has not been explicitly recognized in the maintenance technology development. As the damage events may dependent on two operational parameters such as operation time and number of starts, the two parameters are used as the variables for evaluating probability functions. To provide rational maintenance decision making, risk functions are introduced based on the two-parameter distribution functions and used as the comprehensive measures for synthesizing various damage events occurred in major turbine sections. The examples of some detailed damage scenarios are also presented here to understand the synthetic evaluation of total risks for optimum maintenance planning. This approach could be called as "Damage Informatics" for Steam Turbine Components as a new investigation field of plant integrity.

II. A General Description of Damage Events Observed at Steam Turbine Major Components

Figure 4 shows typical damage modes in steam turbine components [4]. For high-pressure (HP) and intermediate-pressure (IP) turbine rotors, creep damage is accumulated in the bore and wheel hooks. In the dovetail hook contacted area, high cycle or fretting fatigue occurs due to vibratory stress. In the strain concentrations region of casings and valves, cracks initiate due to thermo mechanical fatigue (TMF) during cyclic operations and then grow under internal pressure. For nozzles, downstream deflection of nozzle diaphragm due to steam force occurs at high temperature portion. Solid particle or droplet erosion is sometimes observed in nozzle plates at HP/IP steam inlet portion and wet steam section of LP turbine. For steam pipe weldments, creep damage is accumulated and resulted in the creep void formation. For low pressure turbine rotors, corrosion fatigue or SCC under centrifugal and vibratory stress are typical damage modes.

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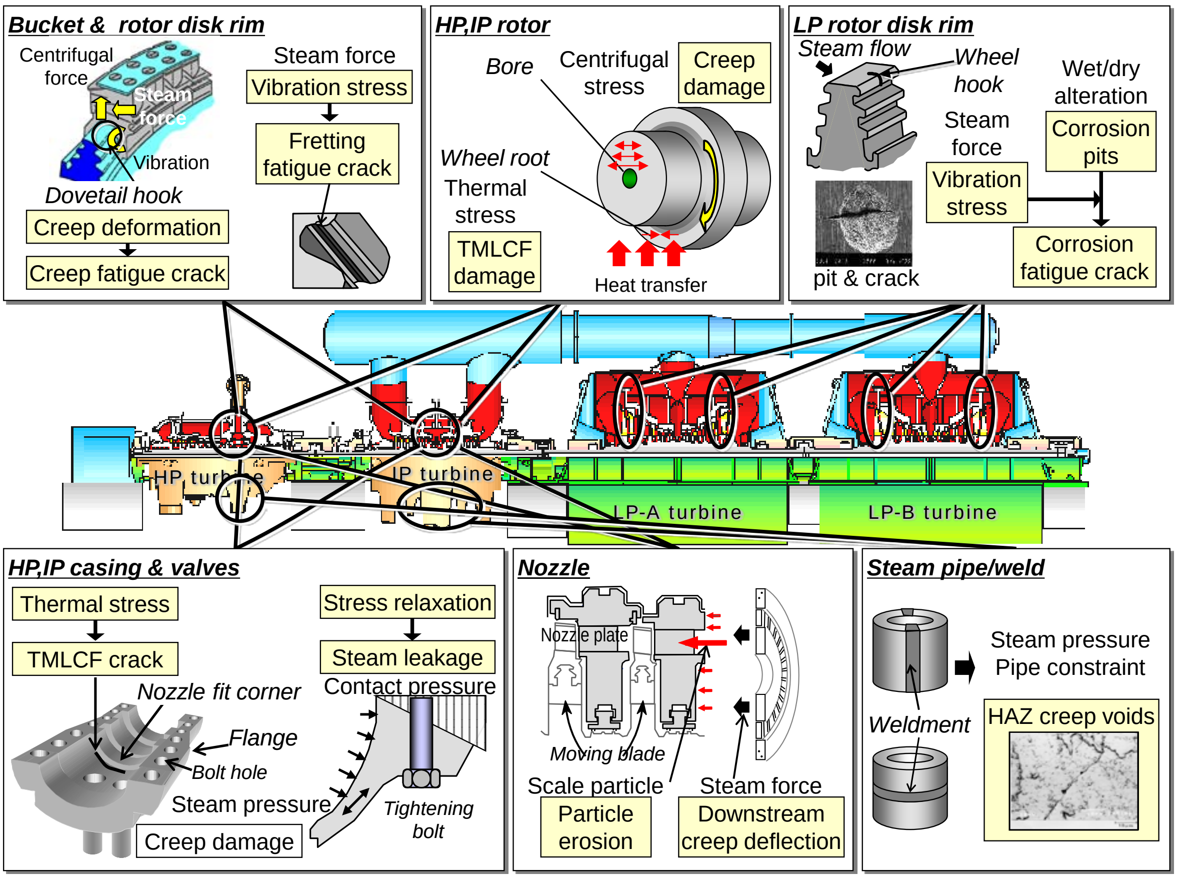

Fig.1 : Damage modes of steam turbine components

III. Statistical Analysis Procedure

Two dimensional log-normal probability distribution function F(Q) is expressed as the following equation and the ellipse locus is obtained by setting Q as a value corresponding to the constant probability[7].

$$F(Q) = 1 - \exp\left(-\frac{Q}{2}\right) \tag{1}$$

$$Q = \frac{1}{1-\rho^2}\left\{\frac{(\ln t - \mu_{Let})^2}{\sigma_{Let}^2} - 2\rho\frac{(\ln t - \mu_{Let})(\ln N - \mu_{LeN})}{\sigma_{Let}\sigma_{LeN}} + \frac{(\ln N - \mu_{Let})^2}{\sigma_{LeN}^2}\right\} \tag{2}$$

$$\rho = \frac{E\{(\ln t - \mu_{Let})(\ln N - \mu_{LeN})\}}{\sigma_{Let}\sigma_{LeN}} \tag{3}$$

Where, μ_{Let}: time based log-normal mean, μ_{LeN}: cycle based log-normal mean, σ^2_{Let}: time based log-normal variance, σ^2_{LeN}: cycle based log-normal variance, ρ: correlation coefficient of $\ln t$ and $\ln N$.

In this article, the value of F is assumed as 0.5 for the convenience in comparison of event data. The relationship between t_{op} and N_s obtained by fitting the mean values of events is defined as the most likely operation pattern from field database and expressed by N_s as the function of t_{op} as follows.

$$N_s = At_{op}^b \tag{4}$$

Substituting Eq.(4) into Eq.(2), we obtain Q expression by t_{op} as follows.

$$Q(t_{op}) = \frac{1}{1-\rho^2}\left\{\frac{(\ln t_{op} - \mu_{Let})^2}{\sigma_{Let}^2} - 2\rho\frac{(\ln t_{op} - \mu_{Let})(\ln A + b\ln t_{op} - \mu_{LeN})}{\sigma_{Let}\sigma_{LeN}} + \frac{(\ln A + b\ln t_{op} - \mu_{Let})^2}{\sigma_{LeN}^2}\right\} \tag{5}$$

For evaluating risks, we must define the values of consequence, but here we put them as unity for the simplicity of data manipulation and then we can sum up the probabilities as the measure of risk value. The resultant risk function r (t_{op}) is expressed by the function of t_{op} as follows

$$r(t_{op})=\sum_{i=1}^{m} C_i F_i(t_{op})=\sum_{i=1}^{m} F_i(t_{op}) \qquad (6)$$

Where, C_i: consequence of failure of event i(assumed=1), m: total number of subject events, $F_i(t_{op})$: probability of failure of event i obtained by Eq.(1).

IV. Marginal Distribution

As the first step, the marginal distribution are obtained against operation tome t_{op} and number of starts N_s as shown in Fig. 2 for high pressure inner casing cracking events. Log-normal type distribution are obtained for most of the event data like this case. The unreliability function of log-normal type is written as follows[2].The variable Y can be put as time of operation t_{op} or number of starts N_s.

$$F(Y)=\Phi\left(\frac{\ln Y-\mu_{Le}}{\sigma_{Le}}\right)=\int_{-\infty}^{Y}\frac{1}{\sigma_{Le}\sqrt{2\pi}}e^{\frac{(\ln x-\mu_{Le})^2}{2\sigma_{Le}^2}}dx \qquad (7)$$

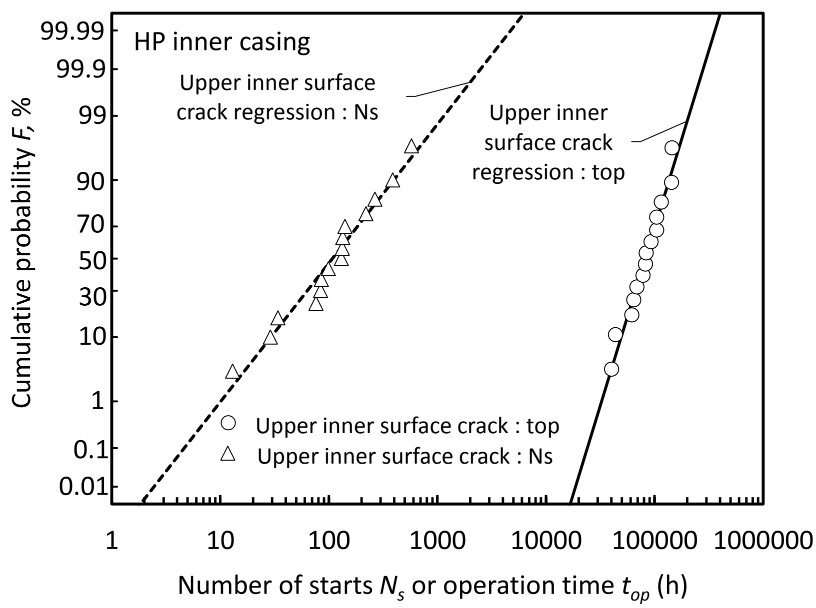

Fig. 2 : Examples of marginal distributions for HP (High Pressure) inner casing cracking event

V. Two-Dimensional Log-Normal Distribution Analysis for Various Events and Casualty Assessment

Based on Eqs.(5) and the marginal distributions obtained in section4, two dimensional log-normal distribution are obtained and then causality assessment can be conducted by using the risk functions of Eq.(6). Individual analytical results for HP (High Pressure) and LP(Low Pressure) turbine sections are described as follows. IP(Intermediate Pressure) turbine section showed almost similar trend with HP turbine section, therefore the IP turbine section was omitted here due to the lack of space.

a) HP (High Pressure) Turbine

Figure 3 shows N_s-t_{op} mean point damage mapping for HP blades and nozzles with 50% unreliability contour. The mean trend is obtained from the regression of mean event data by Eq.(4) excluding HP-2 nozzle erosion which shows irregular plot from the majority trend. This is caused by the data mismatch due to the small number of events (here, only 2 events available but the sets of N_s and t_{op} showed contrary combinations). The orientation of major axis on the N_s-t_{op} plot may represent the tendency for cycle dependence or time dependence. Rather stronger cycle dependences are observed for HP-2 nozzle fouling, HP-2 nozzle deformation, HP-2 nozzle wear, HP-2 blade lifting and HP-2 blade erosion but each does not show the trend clearly enough due to small number of obtained data. On the other hand, HP-1 blade lifting shows more apparent tendency of time dependence compared with other events and it has more data numbers. More detailed event scenario is shown as the flow chart form in Fig.4 referring Fig.3. Resultant risk curve shown in Fig.5 indicates an apparent peak, so the t_{op} value at the peak of risk function can be adopted as the recommendation of inspection timing.

Figure 6 shows N_s-t_{op} mean point damage mapping for HP inner casing plots and almost all data are categorized as the thermo-mechanical fatigue cracking located in the narrow sets of t_{op} and N_s, so there is no motivation to draw mean trend by regression of the data. The shapes of 50% contours show more horizontal orientation which suggests the stronger dependency on number of starts than operation time.

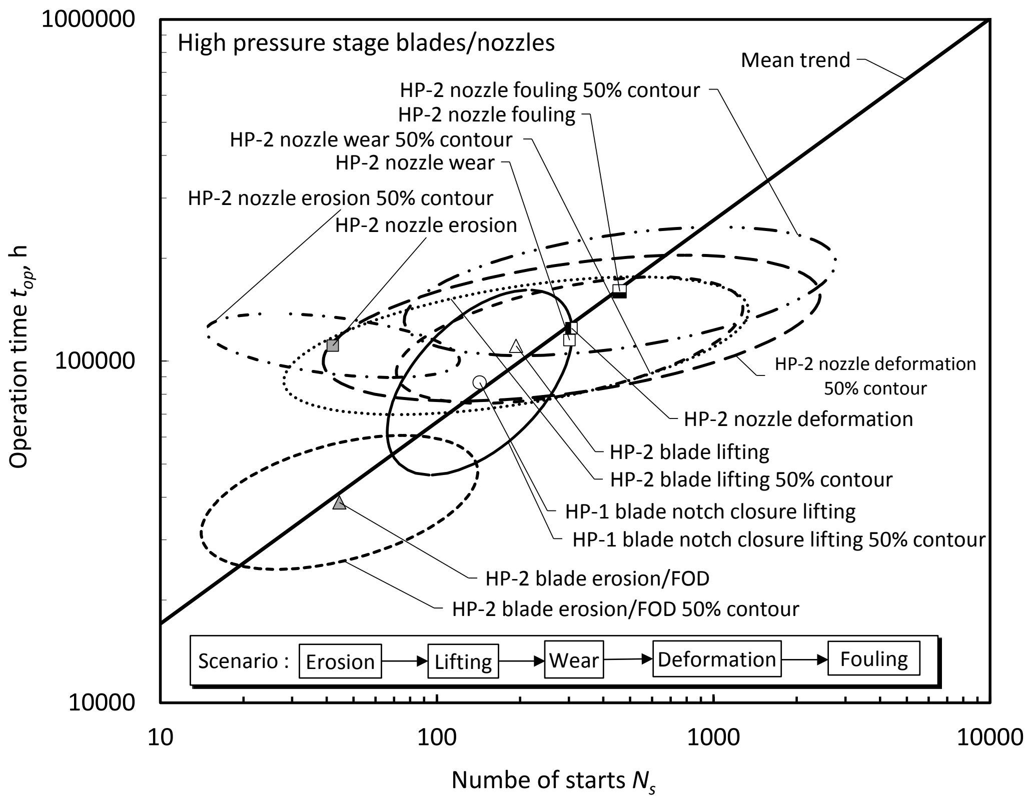

Fig. 3 : Time-cycle damage map for HP blades and nozzles.(HP-1,2:High Pressure Stage 1, 2)

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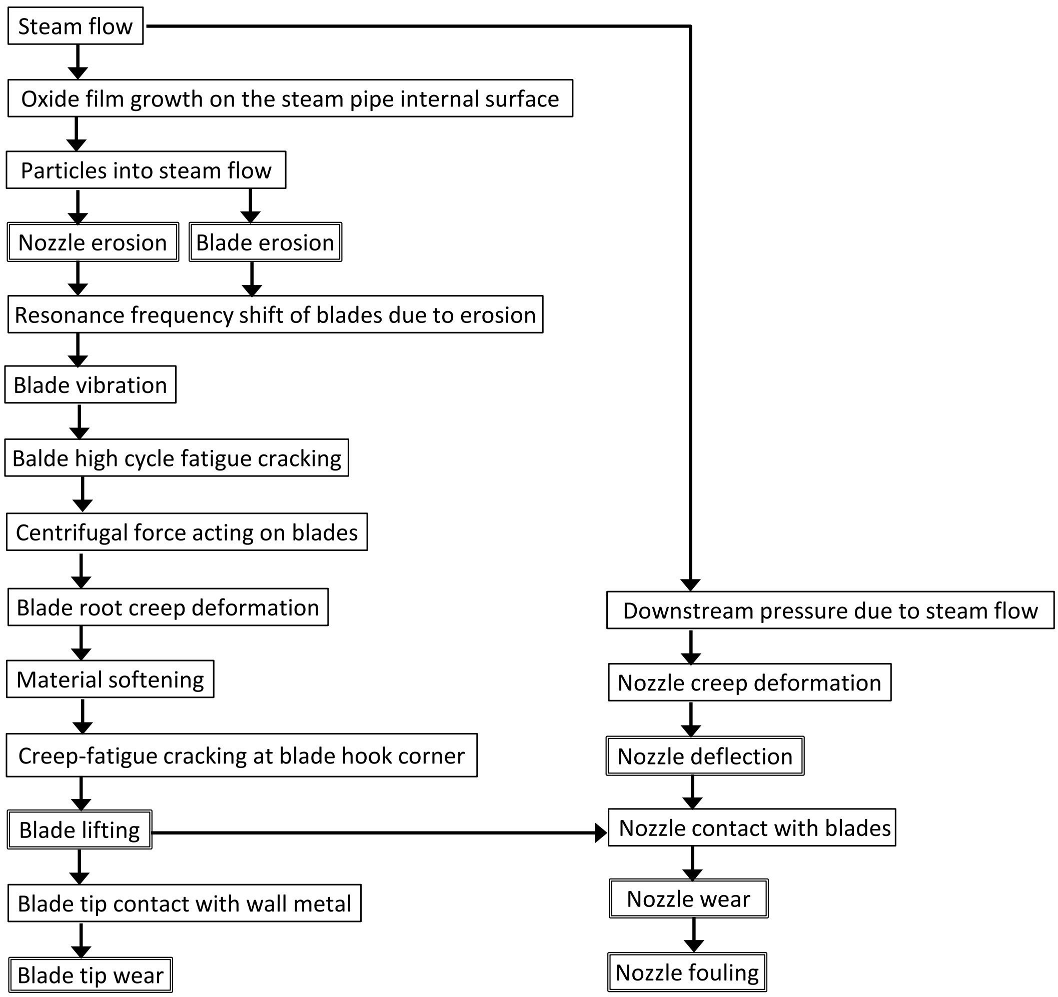

Fig. 4 : Detailed damage flow for HP blades and nozzles (doublets indicate the subtracted events from Fig.3)

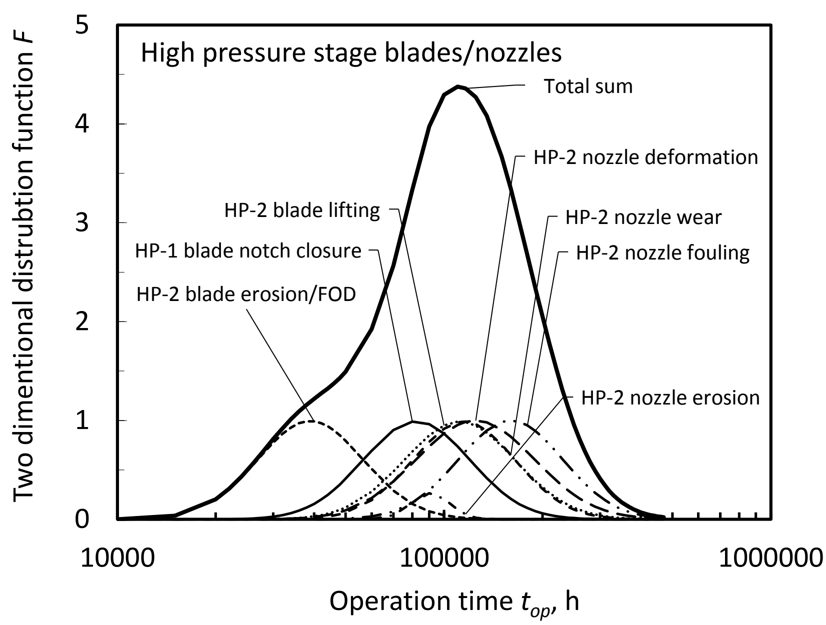

Fig. 5 : Resultant risk curve for HP blades and nozzles

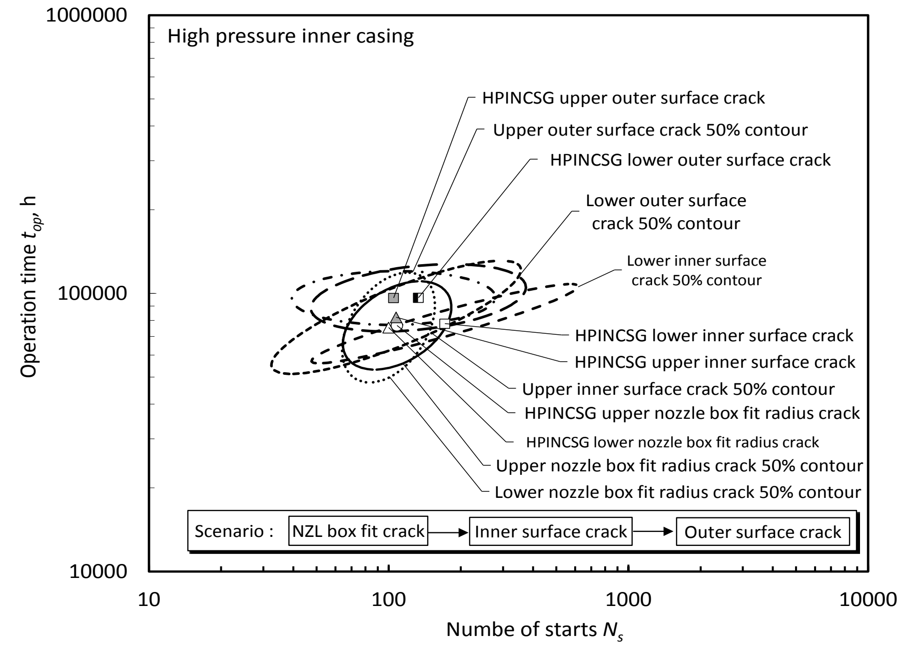

Fig. 6 : Time-cycle damage map for HP inner casings(HPINCSG)

b) LP(Low Pressure) Turbine

Figure7 shows the N_s-t_{op} mean point damage mapping for LP turbine rotor and blades. The majority of events may occur along the mean trend line, and then the sequence can be expressed as early blade damage of erosion/lifting/crack and as the subsequent crack/scoring/erosion damage in rotors. By judging from the 50% failure loci, L-0 blade crack, L-0 erosion shield crack, L-0 lacing wire crack, L-1 lacing wire crack and L-1 shroud crack, show rather cycle dependent than time dependent tendency, but on the other hand, LP rotor journal scoring and L-0 erosion shield erosion show rather time dependent tendency but not so clear. More detailed event scenario is shown as the flow chart form in Fig.8 referring Fig.7. Resultant risk curve shown in Fig.9 indicates an apparent peak, so the t_{op} value at the peak of risk function can be adopted as the recommendation of inspection timing. The optimum timing shows almost similar top value to Fig.5 around over 100,000hours t_{op} which has been recognized widely as the onset of full inspection application.

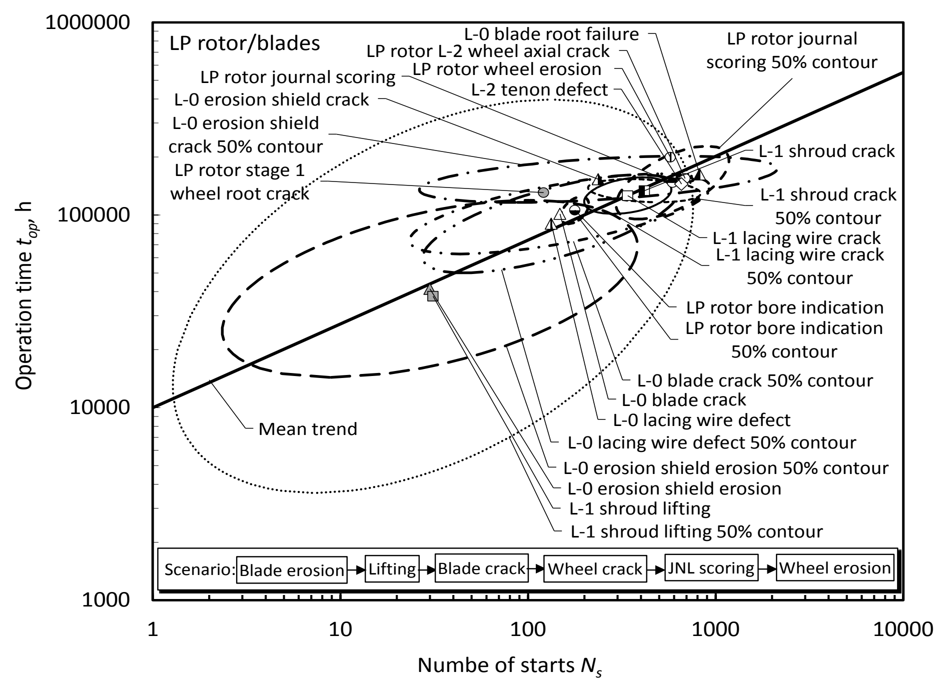

Fig. 7 : Time-cycle damage map for LP rotors and blades (L-0 means the last stage of Low Pressure turbine, L-1 means one stage ahead of L-0 and L-2 means two stages ahead of L-0)

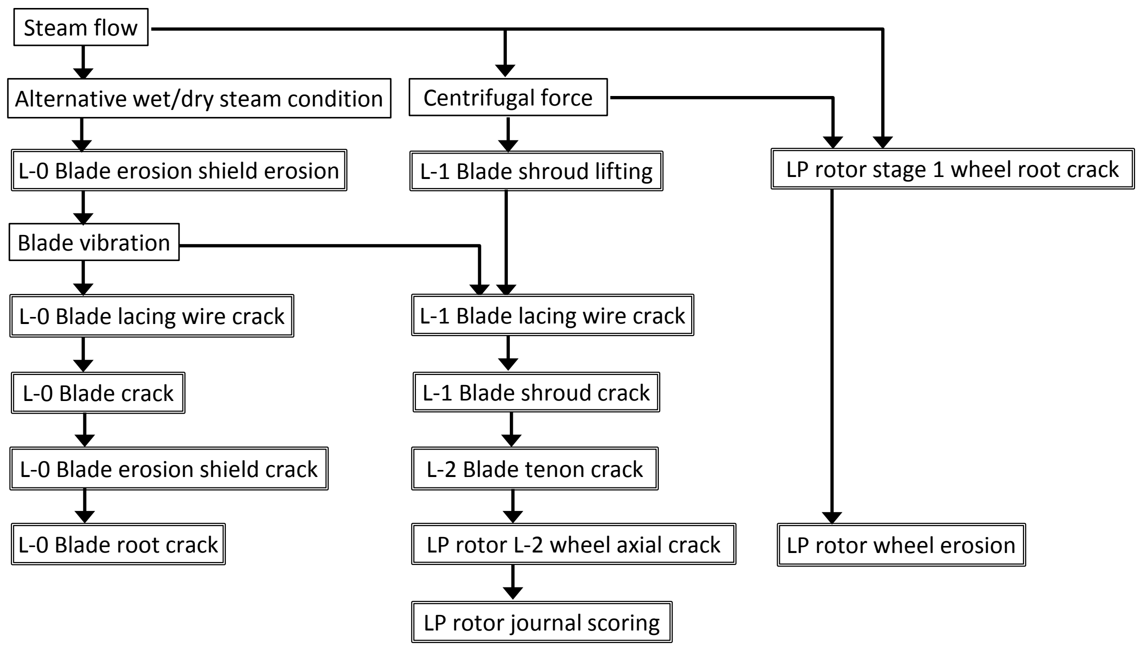

Fig. 8 : Detailed damage flow for LP rotors and blades (doublets indicate the subtracted events from Fig.7)

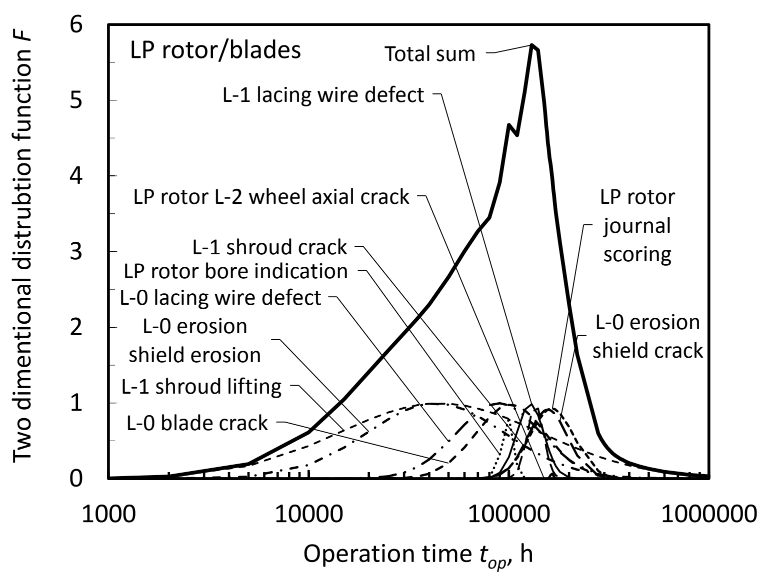

Fig. 9 : Resultant risk curve for LP rotors and nozzles

c) *Risk-cost measures for optimum maintenance planning[8]*

The risk function $r(t_{op})$ in Eq.(6) represents the possible cost for unfavorable damage occurrence and the monotonically increasing function of top. On the other hand, the cost for applying preventive maintenance action is inversely proportional to maintenance intervals. By plotting the risk function and the preventive cost function as shown in Fig.10, we can get resultant cost curves against operation time t_{op}. The resultant curves have minimum points as the recommendation for total predicted cost minimum condition. The timing of these preventive maintenance application is somewhat earlier than the time to peak risk cost which suggests the earlier maintenance can contribute total cost savings.

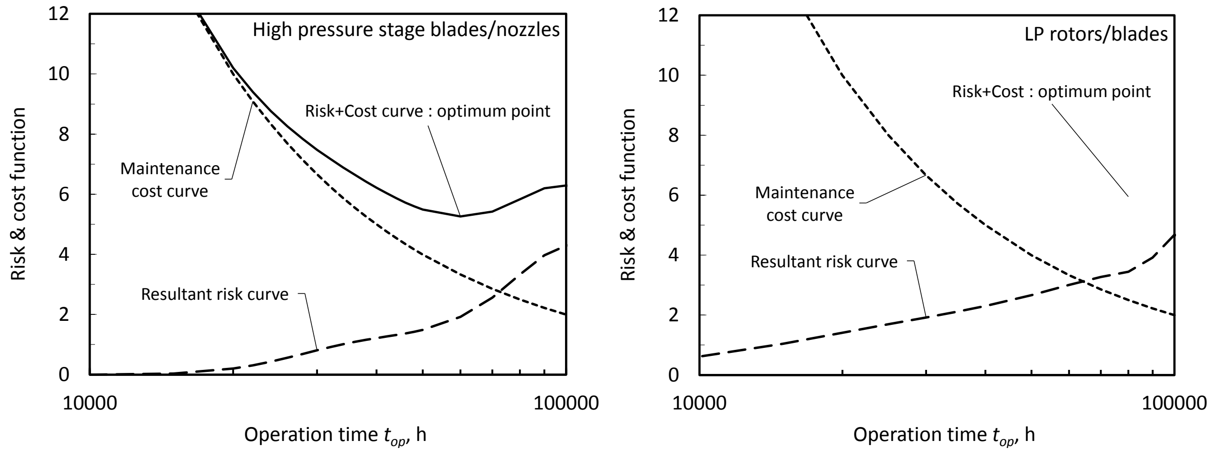

Fig.10 : Schematic risk-cost analysis examples for HP blades/nozzles and LP rotors/blades

VI. Conclusions

Field inspection database can be fully utilized to constitute damage scenario and to make up maintenance decision making for steam turbine major compound sections. Statistical analyses are utilized to quantify the event occurrence timing and the order with the scatter band of each event data. The accumulation of field data is quite important and scenario inference should be performed by combining the data analyses and the knowledge of experts in the form of damage sequence flow chart. The "Informatics" for plant damage may contribute to make more improvement in the accuracy for predicting the life of components and to identify the casualty of the events.

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