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Optimum Material Evaluation of Fan Blades Using Reverse Engineering Approach

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ABSTRACT: *Railway sector is one of the main modes of transport and constitute a significant growth to the development of the country's GDP. The efficient functioning of a diesel locomotive is directly dependent on the efficiency of the cooling system. Railway diesel locomotive engine contains a wide (66") radiator fan, to drive away excess heat from engine jacket cooling liquid. The radiator fan blades are made up of cast aluminum. This paper presents optimum material evaluation of the blade, to explore the causes of failure at junction of blade and flange and to suggest a suitable alternative material for the blade. Static, dynamic and thermal analyses have been carried out separately. In this paper the design data for radiator blade is obtained using reverse engineering technique. Using the data the solid model of the radiator blade is created in ANSYS. The axial thrust and torque loads are applied uniformly at several cross sections of blade, considering the blade as a cantilever beam. Dynamic analysis under pre-stress conditions at full fan speed investigated. Different load variations and material variations are employed to study and propose a suitable material to withstand structural and dynamic loads. Fiber Reinforced Plastic (FRP) material is suggested to Railway Engineering authorities and it is under consideration and testing stage.*

Keywords: *Reverse Engineering, Structural and Thermal Analysis, Radiator blade.*

I. INTRODUCTION

The radiator fan is a device, which sucks the atmospheric air through the radiator panels and expels it to atmosphere to cool the engine coolant after discharge from the engine and maintains an acceptable operating temperature by transferring heat from the engine to the atmospheric air.The radiator fan assembly is fitted at the rear end of the locomotive, which takes drive from the engine through horizontal shaft, eddy current clutch gearbox & universal shaft arrangement (Fig.1). The radiator fan assembly consist of a hub with six blades screwed on its periphery and is mounted on the fan shaft and bearing housing assembly.

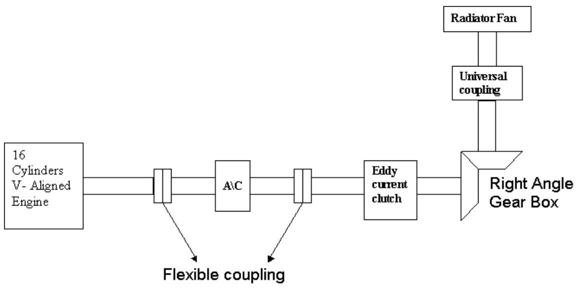


Fig. 1: Locomotive radiator fan drive system.

As an object moves through a fluid, the velocity of the fluid varies around the surface of the object, which induces a centrifugal force on the body. This centrifugal force on the fluid particles on the upper side i.e. convex side tries to move them away from the surface. This reduces the static pressure on this side below the free stream pressure. On account of this "suction effect", the convex surface of the blade is known as suction side.This centrifugal force on the lower side i.e. concave side presses the fluid harder on the blade surface, thus increasing the static pressure above that of the free stream. Therefore, this side of the blade is known as the pressure side. The upward force on the blade is the cumulative effect of the positive static pressure on the pressure side and the negative pressure on the suction side. Due to this pressure difference lift and drag forces are created.

1.1 Drag force

Drag is the force that opposes a fan motion through the air. Drag is generated by every part of the radiator fan assembly. Drag is generated by the difference in velocity between the solid object and the fluid.

There must be motion between the object and the fluid. If there is no motion, there is no drag. It makes no difference whether the object moves through a static fluid or whether the fluid moves past a static solid object. Drag acts in a direction that opposes the motion. As the fan moves through the air, the air resists the motion of the fan; this resistance force is called the drag of the fan. Like lift, there are many factors that affect the magnitude of the drag force including the shape of the body, the "stickiness" of the air, and the speed.

1.2 Thrust force

Thrust is generated most often through the reaction of accelerating a mass of gas. The fan does work on the gas and as the gas is accelerated to the rear, the engine is accelerated in the opposite direction.

II. LITERATURE REVIEW

Pratt and White [1] described the main cause for failure of first stage turbine blades of Space Shuttle Main Engine (SSME). Inspection showed that up to 50% of the blades in several units had cracks in the inside hollow core of the leading edge tips of blades and the failure is a result of one of these cracks growing through the entire wall thickness of the blade. Metallographic inspection of the cracked surface verified that the cracks were due to high cycle fatigue, which can be an indicator of substantial dynamic stress.

IlkerTari [2] discussed one of the important challenges in gas turbine design is cooling of the turbines due to high operating temperature uses. Je – Chin Han and SandipDutta [3] discussed the sophisticated cooling scheme for continuous safe operation of gas turbine with high performance. Gabor Csaba [4] discussed the common failure mode for turbo machinery is high cycle fatigue of compressor and turbine blades, due to high dynamic stresses caused by blade vibration resonance within the operating range of the machinery. Patric B. Lawless [5] has conducted experimental research program to improve the design capability for high-temperature turbines by providing a thorough, detailed understanding and data base of turbine flow fields and their effect on heat transfer.

III. FAILURE ANALYSIS OF BLADE

Even though the number of failures of a particular component may be small, they are important because they may affect the manufacturer’s reputation for reliability. In some cases, particularly when the failure results in personal injury or death, it will lead to expensive lawsuits. In any failure analysis it is important to get as much information as possible from the failed part itself along with an investigation of the conditions at the time of failure.

The possible causes of failures in case of fan blades are as follows.

- Improper heat treatment of the radiator fan blade.
- Pressure variations along the length of the blade.
- Other sundry causes

3.1. Improper heat treatment of the radiator fan blade

Proper heat treatment must be done after casting process i.e., precipitation hardening, so as to increase the strength of the material. The purpose of precipitation hardening is to increase strength and hardness of heat treatable aluminum alloys, and is achieved through a sequence of solution heat treatment, quenching and natural/artificial ageing. However, certain alloys, which are relatively insensitive to cooling rates during quenching, can be precipitation hardened either by air-cooling or by water quenching directly from the elevated temperature shaping process followed by a ageing treatment.

By conducting certain laboratory tests it is observed that that the heat treatment is not done properly and some defects such as

- Pin holes/porosities have been revealed (in clusters at the critical zones and in scattered pattern over other locations of the fan-blades).
- Notches/deep dents have been noticed at and nearby to the hub ends of the fan blades. One can notice that the fractured faces reveal two distinct zones having dull and bright in nature. Fractured faces of the broken blade are completely crystalline in nature.

3.2. Pressure variations along the length of the blade

As the fan is rotating past the fluid (air), this fluid exerts some pressure variation along the cross-section of the blade, due to this pressure changes lift and drag forces will be created, these forces depends upon the design and operating conditions. For the radiator fan, lift force has to be minimum,otherwise it may lead to the breakage of the blade.

3.3 Other Sundry Causes

- The radiator fan of diesel locomotives is required to work in a very hazardous environment with increase of oil dust and rain. It can be exposed to the roadside dust or fiber of various organic materials that can be in the environment of the locomotive operation such as, calcium carbonate, silica sand, aluminum, carbon black, fiber of various organic materials, oil, locomotives brake shoe dust, etc.
- Failures may occur due to cracks generated with the impact of tools, machinery items like clamps, pipes etc during engine overhauling (Fig. 2&3).

Fig.2

Fig.3

IV. REVERSE ENGINEERING PROCESS

If only one original part is available, it has to be handled with utmost care during the process as the original part is crucial for validation. The component must be thoroughly examined and the prominent geometric feature affecting the working of that component must be extracted and the feature which can be measured manually is also estimated. Such features encompass prismatic, geometric shapes. All other features such as free-formed surfaces and complex contours and 3D surfaces and to be measured through other techniques like scanning, acoustics and optical methods. All the dimensions which can be measured manually are taken with the help of available measuring devices like vernier calipers, height gauge, etc. The features which cannot be measured manually can be obtained through any available digitization techniques.

The typical Reverse engineering process can be summarized in sequence as under

- Physical model which needs to be redesigned or to be used as the base for new product.
- Scanning the physical model to get the point cloud. The scanning can be done using various scanners available in the market.
- Processing the points cloud includes merging of points cloud if the part is scanned in several settings. The outlines and noise is eliminated. If too many points are collected then sampling of the points should be possible.
- To create the polygon model and prepare *.stl* files for rapid prototyping.
- To prepare the surface model to be sent to CAD/CAM packages for analysis.
- Tool path generation with CAM package for suitable CNC machine manufacturing of final part on the CNC machine.

V. DIGITIZATIONOF RADIATOR BLADE

First the blade is studied to identify the features for digitizing. The blade is divided into sections accordingly. More number of sections are made at the vicinity of the embossed region and the bent region. Along the identified sections the probing is done to get the point cloud data. The entire outer edge of the blade is digitized to get the size of the point cloud data. The following procedure followed to obtain the coordinate point data.

- Select the suitable probe depending on the complex geometry of blade. Here straight probe of 0.5 mm diameter is used.
- Clamp the blade to restrict the degrees of freedom.
- Selecting the Element option in the main menu of *Usoft* to probe the edge coordinate of the blade root
- Probe at different point along the aero foil section of blade.
- The output file gives the coordinates of probed points along the blade length. These coordinates are taken from fixed reference point.

VI. MODELING OF RADIATOR BLADE

The point cloud data obtained from Digitizing technique imported in *IGES* format into FEA package like ANSYS and solid modeling is done. The key point data for blade is collected from Reverse Engineering process.

VII. DESIGNAND ANALYSIS

The radiator fan blade with the existing material is analyzed first to verify the induced stresses are within the safe limits or not. Further a better alternative material is studied with the same input parameters. The material is chosen in such away that it is least effected to the above said causes of failure. The first part of analysis is to calculate the various forces acting on the blade at different cross sections. Then the blade model is created and analyzed in ANSYS.

Assumptions for the design

- The fluid (air) is considered to be incompressible.
- The turbulent effect i.e., stall conditions are neglected.

7.1. Forces acting on the different sections of the fan blade

On account of considerable variation in the flow conditions and the blade section along the span, it is divided into a number of infinitesimal sections of small, radial thickness. The flow through such a section is assumed to be independent of the flow through other elements.

Velocities and blade forces for the flow through an elemental section are shown in Fig.4. The flow has a mean velocity W and direction β (from the axial direction). The lift force ΔL is normal to the direction of mean flow and the drag ΔD parallel to this. The axial (ΔF_x) and tangential (ΔF_y) forces acting on the element are also shown, (ΔF_R) is the resultant force inclined at an angle ϕ to the direction of lift.

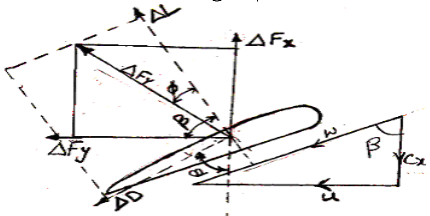


Fig.4

Resolving the forces in the axial and tangential directions,

$\Delta F_x = \Delta L \sin\beta - \Delta D \cos\beta$-------(1)

$\Delta F_y = \Delta L \cos\beta + \Delta D \sin\beta$-------(2)

By definition lift and drag forces from the eq

$\Delta L = ½\, C_a \rho \omega^2 (ldr)$

$= 1/2 \times 0.4588 \times 1{,}225 \times 125.66^2 \times 0.194$

$= 860.845$ N

$\Delta D = ½\, C_d \rho \omega^2 (ldr)$

$= 1/2 \times 0.0.335 \times 1{,}225 \times 125.66^2 \times 0.194$

$= 62.856$ N

From these ΔL and ΔD values the ΔF_x and ΔF_y are calculated from the Eq (1) & (2) as:

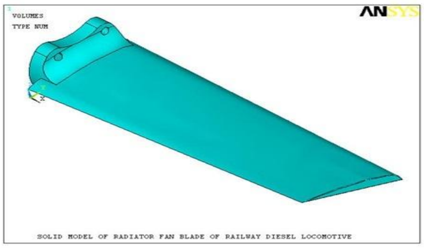
The axial thrust $\Delta F_x = 98.950$ N

The torque force $\Delta F_y = 857.446$ N

Table 1. Axial thrust and torque forces at different radii of the blade

R (mm)	ΔL (N)	ΔD (N)	ΔF_x (N)	ΔF_y (N)
835	860.845	62.856	980950	857.446
750	950.722	75.259	121.956	945.866
650	1078.388	93.781	160.536	1070.488
550	1241.838	121.493	216.744	1228.798
450	1453.648	149.992	315.124	1426.985
350	1730.256	202.359	460.688	1680.030
250	2073.600	268.328	690.958	1973.422
150	2361.815	342.306	913.246	2204.841

7.2. Analysis of Radiator Blade



For present analysis a single blade is imported to ANSYS (Fig.5) in IGES format.The blades are subjected to both thermal and structural loads. The blade is meshed with 3D 10-node tetrahedron thermal elements. The meshed model is as shown in Fig.6. In structural analysis the blade is considered as a cantilever beam (flange end fixed to hub). The loads i.e. the lift and drag forces which are resolved in F_x and F_y directions are applied at various**Fig. 5 Imported blade model in ANSYS** cross sections of the blade obtained (Table.1). The applied loads and boundary conditions on blade are presented in Fig.7.

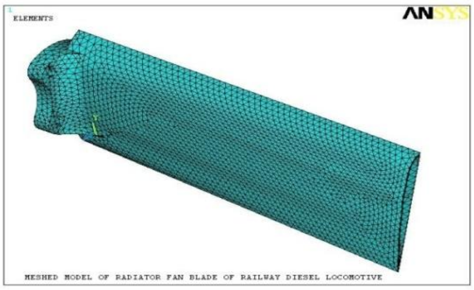


Fig. 6

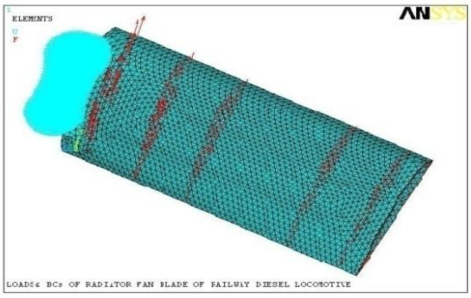


Fig. 7

The analysis is first carried out with the existing blade material i.e. cast aluminum. The maximum deformation and von-mises stress contour plots for cast aluminum material are presented in Fig. 8 and 9 respectively. Thermal analysis is also done on the cast aluminum and FRP and found that there is no marginal rise in the stresses induced on FRP than cast aluminum. The temperature change in the environment from 30^{o}c to 70^{o}c is considered and the analysis is shown in Fig 12 & 13 for cast aluminum and FRP.As an alternative material for radiator blade, Fiber Reinforced Plastic (FRP) is used to replace Cast Aluminum.

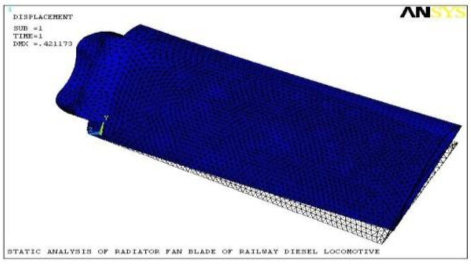


Fig. 8

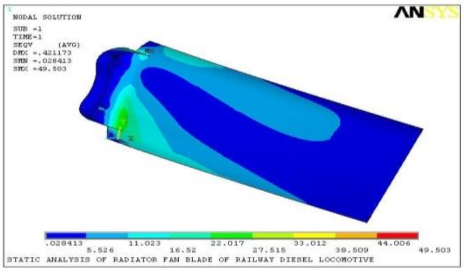


Fig. 9

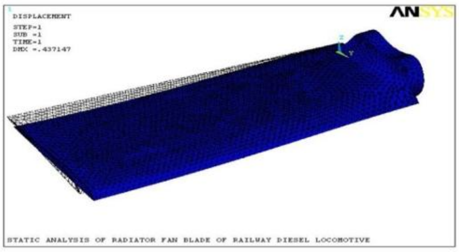


Fig. 10

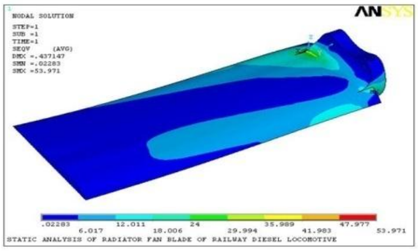


Fig. 11

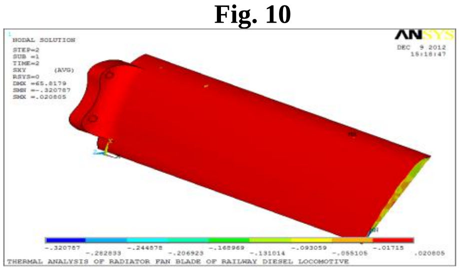


Fig. 12

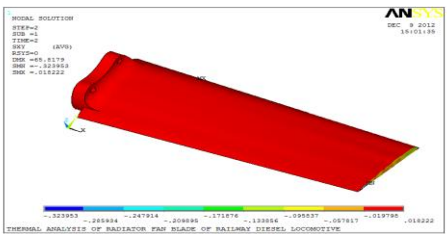


Fig. 13

FRP radiator fan shall be manufactured from isopthalic resin reinforced with a combination of E-glass unidirectional roving, chopped strand mat and woven roving either by RTM (resin transfer moulding) or compression moulding process. FRP radiator fan shall be free from, blowholes, pinholes, porosities etc. Catalyst pigment and accelerator should suit the above resin. The color of the pigment shall be either blue or green. The glass reinforcement used shall not be less than 35% in content.

The above resin has been specified to obtain high tensile and flexural strength, in view of the fact that the standard deviation of tensile strength in FRP is very high. However the resin and reinforcement had to be chosen such that the mechanical properties specified in this specification are met. Fig.10 and 11 represent maximum deformation and von-mises stress contour plots for the considered alternative material Fiber reinforced plastic (FRP).

VIII. RESULTS AND CONCLUSIONS

The maximum deformations of the blade in Global X, Y, and Z directions for existing material and considered materials are presented in Table.2. The induced stresses are tabulated in Table.3. The marginal rise in stresses as well as deformations is observed in case of FRP. But the values are within the safe limits. To prevent the failure of blades due to environmental and other sundry reasons as discussed in article 3, FRP can be considered as suitable alternate material.

Table 2. Static Analysis of Radiator fan blade – Maximum Deformations

Material	**Deformation in mm**			
	X	**Y**	**Z**	**Resultant**
		0.417	**0.015**	**0.421**
Cast Al,2014-T6	**0.102**	**0.148**	**0.004**	**0.148**
Steel,ASTM-A514	**0.036**	**0.420**	**0.005**	**0.424**
Cast Iron,ASTM-A-48	**0.103**	**0.433**	**0.008**	**0.437**
FRP	**0.106**			

Table 3. Static Analysis of Radiator fan blade – Maximum Stresses

Material	**Maximum Stress in N/mm^2**			
	Von-mises	**Shear**	**Principal**	**Thrust direction**
Cast Al	**49.50**	**7.49**	**43.08**	**38.49**
Cast Steel	**52.01**	**7.93**	**42.52**	**37.94**
Cast Iron	**56.05**	**8.63**	**41.79**	**37.19**
FRP	**53.97**	**8.28**	**42.14**	**37.56**

The operating range of the blade is 1210 to 1260 rpm. Hence, the natural frequencies of the blade should not match the frequencies corresponding to these rpm values, which are found to be 20.17 to 21 Hz. Modal analysis is done to find the first five natural frequencies of FRP and are shown in Table 4.The mode shapes of FRP are shown in Fig.14, 15, 16, 17&18.

Table 3. Frequencies of the radiator blade(FRP)

Mode	**Frequency, Hz**
1	**0.88385E-04**
2	**0.41342E-03**
3	**0.51023E-03**
4	**0.56503E-03**
5	**0.11147E-02**

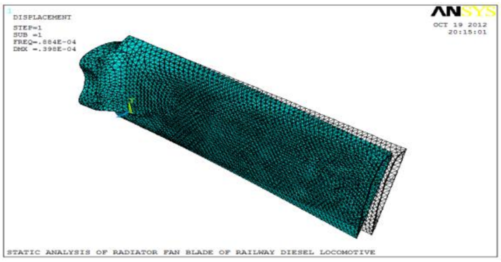


Fig. 14

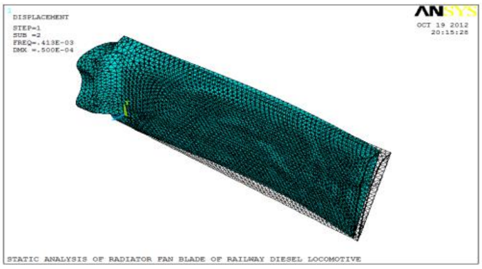


Fig. 15

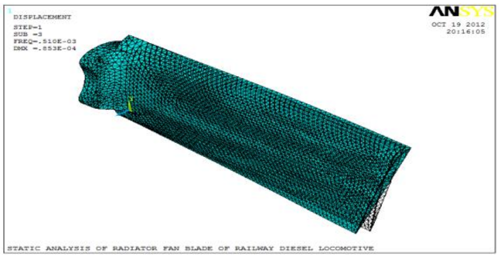


Fig. 16

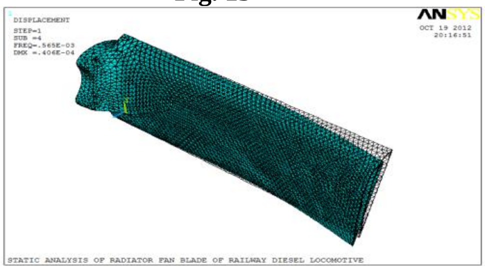


Fig. 17

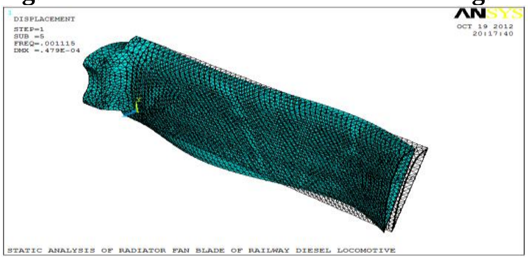


Fig. 18

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