Effect Of Spalling In Different Position Vertically On Mid Span Of Tooth In Mesh

Akhilesh Lodwal, Dr. Ashesh Tiwari

Abstract: Time Varying gear mesh stiffness (TVMS) provides important information about health of a geared system. The spalling created/ developed on gear profile causes change in Time Varying gear mesh stiffness behaviour of the system. In this paper the spalling is assumed in mid of the gear tooth profile anywhere from top of the tooth to the bottom of the tooth and then the effect of change in TVMS by changing in width and height of spall is calculated. The potential energy method is used for the above calculation. This study is done by keeping in mind the vibration behaviour change due to sudden change in gearmesh stiffness. The metrology of gear is used to do calculations. It is found that as the fault occurs near the tip it may give impulse due sharp change in mesh stiffness but as we go towards root side the variation of TVMS is found throughout the contact of teeth. So in all the position of spall may take some span in the dynamic behaviour. Firstly an analytical method is used to calculate stiffness & then the effect of change in stiffness is calculated by varying the geometry of spalling. This paper will help in fault finding of gear analytically and data may be useful for dynamic analysis.

Index Terms–TVMS, Spall

I. Introduction

Gear box is an important element in various industrial and automotive applications. In the gearbox the failure occurs due to excessive stress conditions. There are two types of surface contact fatigue namely pitting and spalling. Pitting appears as shallow craters at the contact surface. The maximum depth of work hardened layer is approximately 10 micro meter. Spalling appears as deeper (20-100 micro meter) cavities at contact surface with a depth of 0.25 to 0.35 of contact width [1]. As per the research the spalling grows after three stages. Initially crack develops due to inclusion of hard particle or material defect. During contact the repeated stress develops causes more development of crack that finally result in the surface deterioration [6]. In different literature spalling and pitting were used to designate severities of surface fault. In our case we have assumed a square cavity at the mid of span at different position vertically. Gear mesh stiffness is the combined stiffness experienced when two a gear pair is in mesh. The time varying gear mesh stiffness represent the state of tooth deterioration & affect the gear vibration [2]. When the cracked tooth come in contact during meshing the mesh stiffness reduces Further as the crack length increases due to the periodic sudden changes and time varying mesh stiffness the impulsive change occurs in the dynamic behaviour. When the cracked tooth come in contact the amplitude will increase as a result of reduction of mesh stiffness. This occurs one in the rotation of the gear and causes vibration in the gear at equal to the rotating frequency of gear [6]. So finding of time varying stiffness is an important task in fault finding of gearbox.

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The most widely used technique for finding the time varying mesh stiffness is the Finite element method [3], but the expertise on software is required to be developed. Also the mesh refinement, model preparation and finding correct way in total is a time consuming job. An ISO Standard 6336-1-2006 defines a method to calculate the mesh stiffness but can only calculate the single stiffness and average mesh stiffness [3]. For the analysis of the effect of spalling the gearmesh stiffness is an important parameter that is studied and calculate analytically by so many researchers. For the analytical calculation different parameter of the gear tooth were measured and used to find a particular type of stiffness. The researcher have worked on the bending stiffness, shear stiffness, axial stiffness, fillet foundation stiffness, contact stiffness time by time and get so many outcome related to their working condition. The potential energy method is widely used method in which the gear tooth was assumed as a variable cross section cross section beam fixed om gear circle[2].Healthy tooth mesh stiffness were calculate by weber (1949), Attia (1963), Kasuba and Evans (1981) and corneli (1981). Yan and lin (2004) calculated the TVMS of gear pair using potential energy method inclusing Hertzian, bending and axial compressive stresses. Tian and Wu modified their model by taking shear stiffness ratio in consideration. An important outcome occurs from theory that when the number of teeth are less than 42 the base circle is larger than the root circle. So energy stored between the root & base circle plays an important role that is also studied by the earlier researcher.

II. Methodology

For calculation of gearmesh stiffness (TVMS) due to spalling a gear tooth having spalling defect at mid span is considered as shown in figure 1.

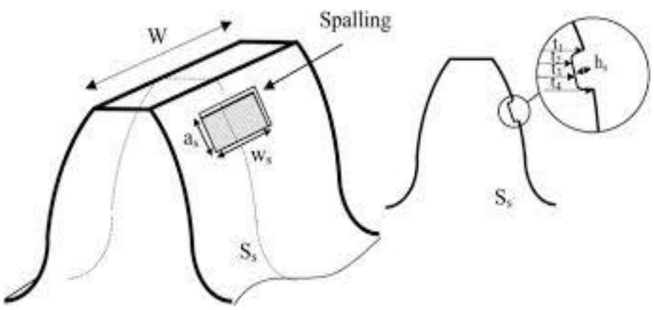


Figure 1. Spalling defect at mid span.

Here W is the width of gear, Ws denote the width of spall, hs denotes the depth of spall and a_s the length of spall. In this analysis the spall area once decided, kept at three different position in the mid span from face to flank for covering the effect on Time varying mesh stiffness from top to bottom using following relation [1].

Equivalent mesh stiffness for no of tooth pair in contact considering contact deflection bending deflection, axial deflection and shear deflection are as follows.

$$K_{total} = \sum_{i=1}^{2} \frac{1}{\frac{1}{K_{hi}}+\frac{1}{K_{b_{1i}}}+\frac{1}{K_{s_1}}+\frac{1}{K_{a_{1i}}}+\frac{1}{K_{b_{2i}}}+\frac{1}{K_{s_{2i}}}+\frac{1}{K_{a_2 i}}} \quad \text{------(1)}$$

Using the data mentioned in the specification the above stiffness are calculated using following relations.

a) Contact Stiffness: In case of Healthy Gear the contact stiffness is calculated by

$$K_h = \frac{\pi E W}{4(1-\mu^2)} \quad \text{---------(2)}$$

For gear having spall of width Ws, the contact stiffness can be calculated by the relation given below. In this case the contact stiffness reduced when the spalling is present.

$$K_h = \frac{\pi E (W-W_s)}{4(1-\mu^2)} \quad \text{------------(3)}$$

b) Bending Stiffness: For the calculation of bending stiffness the gear teeth is Assumed to be a cantilever beam fixed on the base circle as shown in the figure 2. In this case the gear face and flank portion is divided in three parts & the analytical calculation was done accordingly.

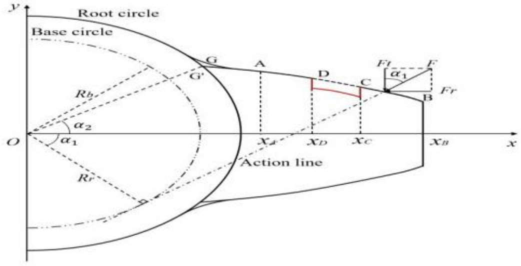


Figure -2: Position of spall on gear teeth [1]

The Potential energy in case of bending for gear tooth with spalling when the spall is present in different region are as follows:

$$\text{Ub} = \int_{x_A}^{x_\beta} \frac{{M_1}^2}{2EI_1} dx_1 \qquad x_A < x_\beta < x_D$$

$$\text{Ub} = \int_{x_A}^{x_D} \frac{{M_1}^2}{2EI_1} dx_1 + \int_{x_D}^{x_\beta} \frac{{M_2}^2}{2EI_2} dx_2 \qquad x_D < x_\beta < 5)$$

$$\text{Ub} = \int_{x_A}^{x_D} \frac{{M_1}^2}{2EI_1} dx_1 + \int_{x_D}^{x_C} \frac{{M_2}^2}{2EI_2} dx_2 + \int_{x_C}^{x_\beta} \frac{{M_3}^2}{2EI_3} dx_1 \qquad x_C < x_\beta < x_B$$

------------------------- (4)

The moment applied by the force at different position are given by

$$M_1 = F_t(x_\beta - x_A) - F_r y_\beta \qquad x_A < x_\beta < x_D$$
$$M_2 = F_t(x_\beta - x_D) - F_r y_\beta \qquad x_D < x_\beta < x_C$$
$$M_3 = F_t(x_\beta - x_C) - F_r y_\beta \qquad x_C < x_\beta < x_B$$

Here $F_r = F \sin \alpha_1$, $F_t = F \cos \alpha_1$ are the tangential and radial force by driver during mesh.

------------------------- (5)

The Inertia offered by the loaded area can be calculated by:

$$I_1 = \frac{2}{3} {y_1}^3 w \qquad x_A < x_\beta < x_D$$
$$I_2 = \frac{2}{3} {y_2}^3 w - \left[\frac{1}{12} {h_s}^3 w_s + (y_2 - \frac{h_s}{2}) w_s h_s\right] \qquad x_D < x_\beta < x_C$$
$$I_3 = \frac{2}{3} {y_3}^3 w \qquad x_C < x_\beta < x_B$$

-------------- (6)

The bending Stiffness of the teeth can be calculated by using the relationship.

$$K_b = \frac{F^2}{2U_b}$$

------------ (7)

Shear Stiffness Calculation: The Potential energy in case of shear for gear tooth with spalling when the spall is present in different region are as follows:

$$\text{Us} = \int_{x_A}^{x_\beta} \frac{1.2{F_t}^2}{2GA_1} dx_1 \qquad x_A < x_\beta < x_D$$

$$Us = \int_{x_A}^{x_D} \frac{1.2{F_t}^2}{2GA_1} dx_1 + \int_{x_D}^{x_\beta} \frac{1.2{F_t}^2}{2GA_2} dx_2 \qquad x_D < x_\beta < x_C$$

$$Us = \int_{x_A}^{x_D} \frac{1.2{F_t}^2}{2GA_1} dx_1 + \int_{x_D}^{x_C} \frac{1.2{F_t}^2}{2GA_2} dx_2 + \int_{x_C}^{x_\beta} \frac{1.2{F_t}^2}{2GA_3} dx_3 \qquad x_C < x_\beta < x_B$$

------------------------- (8)

The effective area can be calculated by

$$A_1 = 2y_1 w \qquad x_A < x_\beta < x_D$$
$$A_2 = 2y_2 w - h_s w_s \qquad x_D < x_\beta < x_C$$
$$A_3 = 2y_3 w \qquad x_C < x_\beta < x_B$$

------------------------- (9)

The bending Stiffness of the teeth can be calculated by using the relationship.

$$K_s = \frac{F^2}{2U_s}$$

c) Axial Stiffness: The Potential energy in case of shear for gear tooth with spalling when the spall is present in different region are as follows:

$$\int_{x_A}^{x_\beta} \frac{F_r^2}{2EA_1} dx_1 \qquad x_A < x_\beta < x_D$$
$$\int_{x_A}^{x_D} \frac{F_r^2}{2EA_1} dx_1 + \int_{x_D}^{x_\beta} \frac{F_r^2}{2EA_2} dx_2 \qquad x_D < x_\beta < x_C$$
$$\int_{x_A}^{x_D} \frac{F_r^2}{2EA_1} dx_1 + \int_{x_D}^{x_C} \frac{F_r^2}{2EA_2} dx_2 + \int_{x_C}^{x_\beta} \frac{F_r^2}{2EA_3} dx_3 \qquad x_C < x_\beta < x_B \quad \text{------------------------- (10)}$$

The Axial Stiffness of the teeth can be calculated by using the relationship

$$K_a = \frac{F^2}{2U_a} \quad \text{------------------ (11)}$$

IV Analytical Calculations:

To calculate the mesh stiffness due to spalling defect a gear pair is used. The modelling of the gear pair was done on Creo 3.0. The specifications are as follows [9].

No. of teeth in gear	30
No. of teeth in pinion	25
Pressure angle	20^0
With	20 mm
Module	2 mm
Modulus of elasticity	210 GPa
Modulus of Rigidity	79.8 GPa
Poisson's Ratio	0.3

For the calculation a torque 28.13 N-m corresponding to a force of 1000 N is applied on the gear as well as pinion. The above data is used to find bending Stiffness, shear stiffness, axial stiffness and contact stiffness for tooth on individual gear and the combined effect during meshing are obtained by finding equivalent stiffness. The change in stiffness is observed by changing the width and the depth of spalling in the following manner.

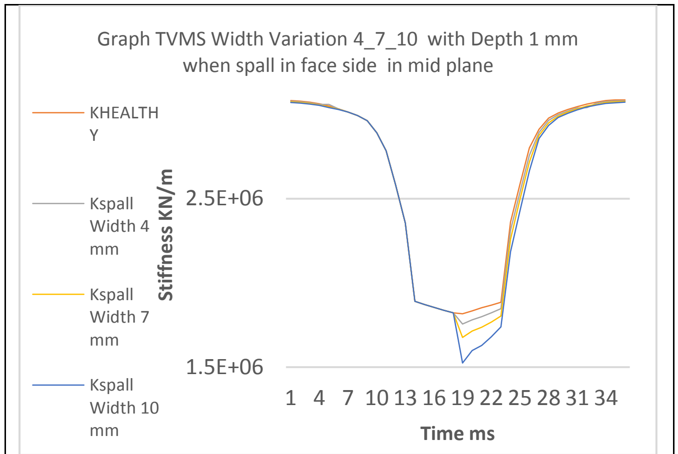
The spall is created at three position based on the division of profile in three equal part. First the spall is created on face, second on mid span (face-flank portion) and third on the flank of the teeth

This paper is focused on the effect of spalling if it is present anywhere in the face, flank or face-flank portion in mid of the tooth width. For the calculation a program on MATALAB is developed using above mathematical formulas. The important one in this paper is the study on vertical portion of tooth profile in mid plane that gives outcome those are very much useful for research as well as fault diagnosis.

The depth and width variation are observed by fixing one parameter and varying another within limit.

V. RESULTS AND DISCUSSION

Spall in Upper part of teeth in mid width.



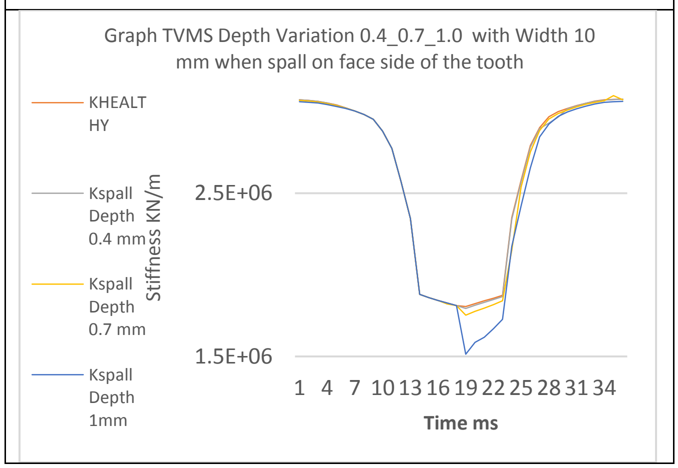
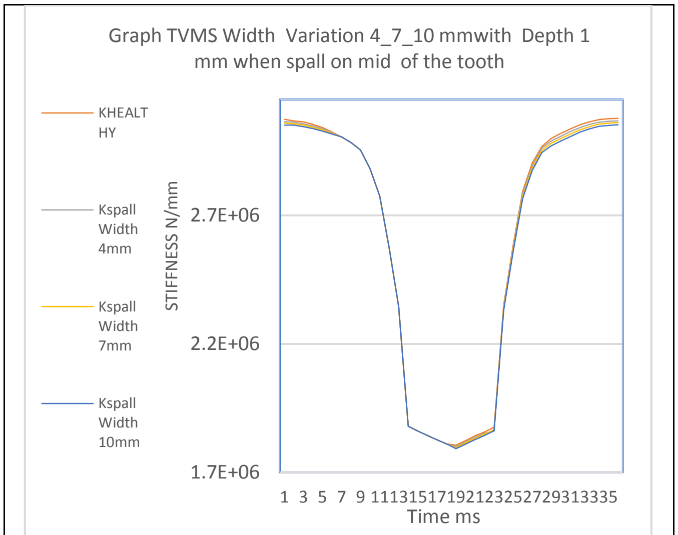


Figure: 1 Effect of Spalling in upper part of teeth on TVMS of gear pair by variation of width & Depth of spall.

From figure no.1 it is observed that when the width of the spall increases the value of stiffness decreases as suddenly when the spallled portion of gear tooth come in contact. The width of spall considered 10 mm and the depth of spall increases from 0.4 mm to 1.0 mm with mid value of 0.7 mm. When the contact occurs between healthy-healthy part of the teeth the TVMS is calculated & shown in figure. When the contact occurs between healthy & defective part the stiffness decreases maximum by 0.6%, 2.9% and 16.1 % maximum compared with the healthy teeth contact for the spall depth of 0.4, 0.7, 0.1 mm show In the lowest part of the graph.

Similar variation are observed when the width of spall increases from 4 mm to 10 mm with mid value of 7 mm. The depth of spall kept 1.0 mm constant. When the contact occurs between healthy-healthy portions of teeth the TVMS is calculated & shown in figure. When the contact occurs between healthy & defective part the stiffness decreases maximum by 3.4%, 7.7% and 16.1 % maximum compared with the healthy teeth contact for the spall width of 4, 7, 10 mm. .Lots of variation occurs mainly when the tooth contact begins.

Spall in mid part of teeth in mid width.



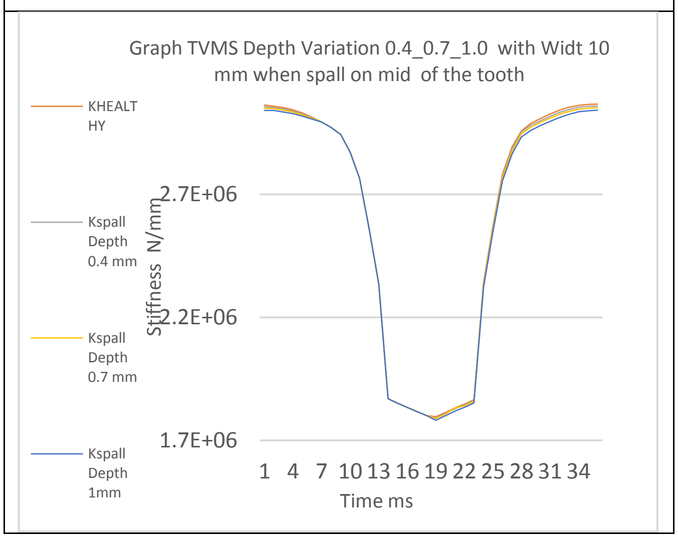
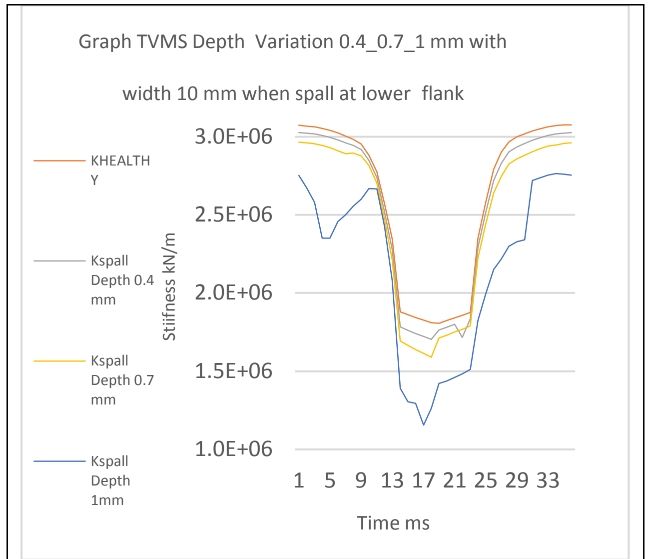


Figure: 2 Effect of Spalling in mid (face-flank) on TVMS of gear pair by variation of width & Depth of spall.

From figure no. 2 it is observed that the value of stiffness decreases as width of the spall increases as the tooth is weak at the center and deflection is more. The Depth of spall kept 1 mm constant and width of spall increases from 4 mm to 10 mm with mid value of 7 mm. In the figure 2 the TVMS graph is shown when the contact occurs between healthy-healthy parts of the teeth. But when the contact occurs between healthy & defective part of the teeth stiffness decreases maximum by 0.29%, 0.55%, and 0.98% for the spall width of 4, 7, 10 mm.

In the similar condition when the depth of spall increases from 0.4 mm to 1.0 mm with mid value of 0.7 mm. The width of spall kept 10 mm constant. It is observed that when the contact occurs between healthy & defective part the variation in TVMS is negative with the maximum value of 0.32%, 0.61%, and 1.03% for the spall depth of 0.4, 0.7, 0.1 mm.

Spall in lower part of teeth in mid width.



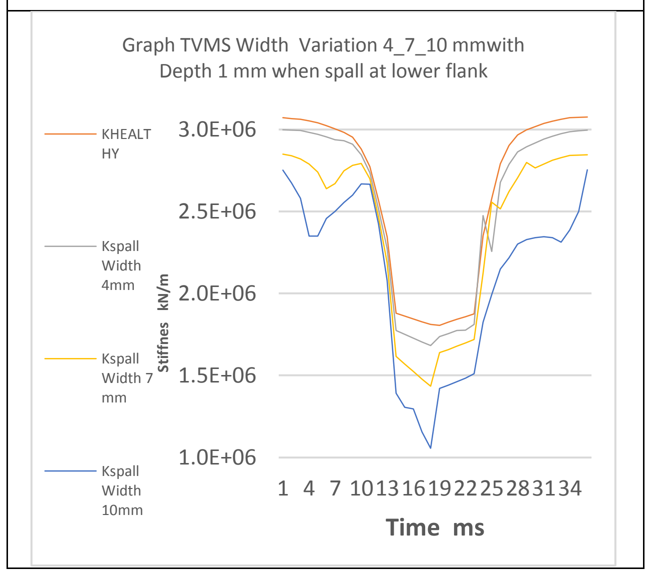


Figure: 3 Effect of Spalling in lower part of teeth on TVMS of gear pair by variation of width & Depth of spall.

The figure shows that the values of Time varying mesh stiffness when the spall is created in the root side/ in flank/ below pitch circle. The spall created is of constant width of 10 mm and the depth increases from 0.4 mm to 1.0 mm with mid value of 0.7 mm. When the contact occurs between healthy-healthy parts of the teeth the TVMS is calculated & shown in figure. In this case when the spall is created in the root side the effect of decreased TVMS is seen on the overall contact period of tooth. The maximum effect occurs when the tooth contact begins and leaves. The maximum variation is 2.4%, 5.2%, 21.3% when the depth increases as 0.4 mm, 0.7 mm, and 1.0 mm respectively. So the effect of low TVMS occurs for maximum time as whole tooth contact occurs at less mesh stiffness.

In the similar condition when the spall is created of constant depth and the width is increased by 4mm, 7mm and 10 mm compared to healthy. We get quite similar behavior but the percentage variation are different. In this case again the effect of decreased TVMS is seen on the overall contact period of tooth. The maximum effect occurs when the tooth contact begins and leaves. The maximum variation occurs are 3.9 %, 9.3%, and 21.3% when the width increases as 4 mm, 7 mm, and 10 mm respectively. So again the effect of low TVMS occurs for maximum time as whole tooth contact occurs at less mesh stiffness.

VI Conclusion:

By conducting the above study it is observed that the effect of spalling in depth as well as in width affect the mesh stiffness of gear pair.

This effect of change in stiffness is noticeable and can be used as parameters of fault diagnosis for the gear tooth pair. The effect on vibration behavior [6] can also be predicted from the above outcome. As the spall position move from top to bottom of the teeth the variation occurs more pointed when the spall is at the upper side of tooth but for very short time. But when spall occurs in the lower part overall more variation is seen on the TVMS behavior, so two different type of vibration pattern may be obseverd while studying in dynamic part. . This effect can also be extended to calculate the vibration as well as noise noise level for condition monitoring of different types of gear box.

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