Identification of contact regimes in mechanical components for the evaluation of fretting damage

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ABSTRACT. In this work the regimes of contact in misaligned crowned splined couplings have been analyzed. Experimental tests have been performed in order to identify if fretting damage on the components appears as fretting wear or fretting fatigue.
A significant difference was identified on the surface of specimen by analyzing two different tests; the first test emphasized a fatigue damage and in the second test a wear phenomena has been achieved.
Also a good correlation has been obtained by analyzing the fretting map obtained by using the Mindlin's theory and experimental results.

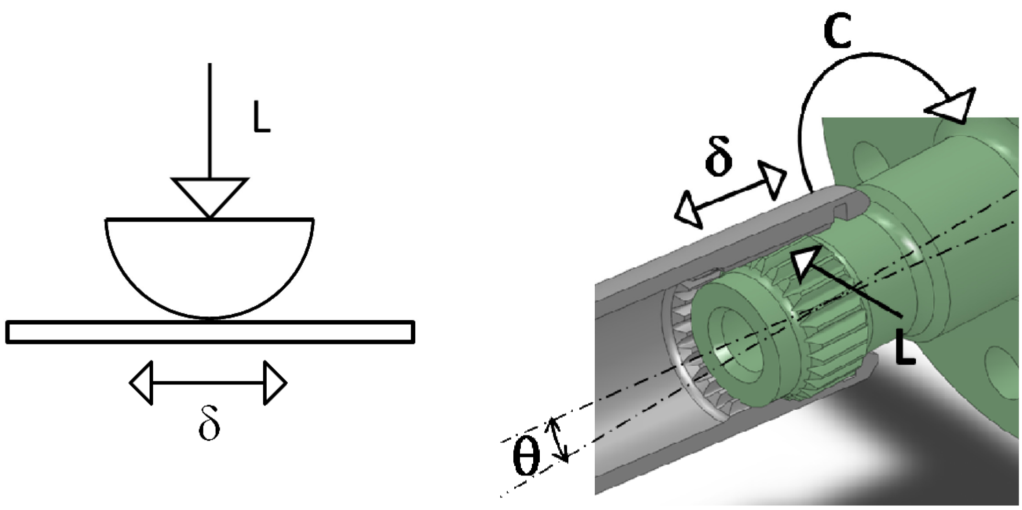
SOMMARIO. In questo lavoro sono stati analizzati i regimi di contatto di accoppiamenti scanalati bombati che lavorano in condizioni disallineate. Specifiche prove sperimentali sui componenti sono state svolte al fine di determinare quale tipologia di danneggiamento da fretting (wear o fatica) compare.
Una differenza di danneggiamento significativa sulle superfici dei denti dei provini è stata identificata analizzando due prove sperimentali; nella prima prova è stato riscontrato un danneggiamento a fatica mentre nella seconda prova si è rilevato un fenomeno di usura.
Inoltre è stata riscontrata una buona correlazione tra la mappa da fretting ottenuta utilizzando la teoria di Mindlin e le prove sperimentali svolte.

KEYWORDS. Spline coupling; Fretting map; Wear; Fretting.

INTRODUCTION

In recent decades, the progresses in technology have led to further improvements in machine performance in terms of power, dynamic behavior and weight reduction; on the other hand, they have led to the emergence of new types of damage, as an example that knowing as fretting.
Fretting is a phenomenon not easy to understand and quantify, which creates big problems to producers and users of machines in many industrial sectors (aerospace, rail, automotive, biomedical, etc.). Currently design criteria for components doesn't considered fretting damage.
For these reasons, in recent years, an increasing interest is growing for the study of the fretting, both in scientific community and in industrial sector.
Fretting appears when two bodies in contact, pressed by a force, undergo small displacements and this friction leads to the rise of damage.
This phenomenon is divided into two categories: fretting wear and fretting fatigue. It is in general very tricky and dangerous, as components that are statically and fatigue verified (or even oversized) may be subjected to an onset of fretting that, once triggered, is a degenerative process leading to the failure of the component.

A premature failure due to fretting may be attributed to either rapid crack growth (fretting fatigue) or surface wear (fretting wear).
Because of the general difficulty of formulating a quantitative model for fretting damage until today robust verification procedures for simplified models of contact are not commonly utilized. This study is even more complicated considering components with complex geometries, as splined couplings.
Splined couplings are then frequently employed in mechanical transmission systems for aeroengine applications because of their high specific torque transmission capacity and ability to tolerate some misalignment and movement [1].
Splined connections can accommodate appreciable shaft misalignments; hence it is customary to use such connections when shaft misalignment is anticipated. However, when misalignment occurs, the resulting oscillatory relative motion between the engaged splines may result in significant damage.
Splined couplings are frequently cited as complex assemblies that experience fretting damage [2, 3], both wear and fatigue. The loading conditions that may rise to fretting wear, fretting fatigue or fatigue in such a coupling have been investigated [4–6].
Fretting wear is typically more gradual and progressive, compared with the above-mentioned fatigue failures. However, it can significantly add to the maintenance cost of an aeroengine. The fretting wear of spline couplings has received limited attention with studies initially concentrating on both wear and friction of straight flat sided splines [7-9].
During the last decade, the extension of numerical methods to contact problems involving friction made possible to predict surface and subsurface stresses on the spline teeth under general loads and to determine contact pressure and slip distributions across the contacting spline surfaces.
In this work the regimes of contact in crowned splined coupling has been analyzed and experimental tests have been performed on order to identify if fretting damage on the components appears like fretting wear or fretting fatigue.
Fig. 1 shows the difference between a fretting test for the fretting material characterization, performed by means of a simplified contact geometry, (Fig. 1a) and the working condition of a spline coupling (test article) (Fig. 1b): the angular misalignment α causes a relative sliding δ between teeth and the transmitted torque T generates a contact force F shared between teeth. Considering a real component, it is necessary to identify the actual regime of contact and so on the correct load conditions [10], the respective contact pressure distribution [11] and the relative motions between parts given by the kinematic equations of the components.



(a) (b)

Figure 1: Fretting tests on materials (a) and components (b).

The different domains of the sliding conditions are identified depending on the normal force and the displacements and may be identified by means of fretting maps (Fig. 2) [12].
Following the Mindlin approach [13, 14], a fretting map has been obtained for the considered splined coupling specimens (see Fig. 3).

FRETTING MAP

The "fretting map" approach confirms that the fretting damage evolution depends strongly on the fretting regime [15, 16]; this graph represents the displacement amplitude of the two surface in contact versus the normal load that is applied to guarantee the contact of the two bodies. Thanks to this, in function of the coefficient of friction, it is possible to determine what kind of fretting phenomena will be appear.

In general it is important to predict if the working condition of components (in particular this work refers to splined couplings), brings to fretting fatigue or to fretting wear damage. This difference substantially depends on the sliding regimes (partial slip or gross slip) involving transmitted torque, coefficient of friction and sliding amplitude [17, 18].

As described by Mindlin [13, 14] for the theoretical case of sphere/plane contact, partial slip corresponds to a composite contact where a central stick domain is surrounded by a pulsing sliding annular domain while, when gross slip occurs, the initial partial slip evolution is followed by a full sliding period. During this stage the contact is characterized by a constant friction force associated with a pure dissipative behavior.

In order to calculate the threshold transition between gross and partial slip, an appropriate program has been developed. This program is able to calculate the sliding conditions as a function of the spline coupling geometry and it allows the corresponding fretting map.

Equations proposed by Mindlin [13, 14] have been used to obtain the fretting map for the spline coupling; in particular the displacement (δ) may be obtained as follow:

$$\delta = \mu \cdot P^{\frac{2}{3}} \cdot K_1 \cdot \sqrt[3]{\frac{4 \cdot E}{3 \cdot R}} \tag{1}$$

With

$$K_1 = \frac{3}{16} \cdot \left[\left(\frac{2-\upsilon_1}{G_1} \right) + \left(\frac{2-\upsilon_2}{G_2} \right) \right] \tag{2}$$

$$\frac{1}{E} = \frac{1-\upsilon_1^{\ 2}}{E_1} + \frac{1-\upsilon_2^{\ 2}}{E_2} \tag{3}$$

and

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

where μ is the static friction coefficient, P the normal force, E_1 and E_2 are Yong's elastic moduli, R_1 and R_2 are radii of curvature of the surface in contact, υ_1 and υ_2 are Poisson's ratios coefficient and G_1 and G_2 are shear moduli.

The contact behavior is then defined by an hysteresis normal force P versus displacement δ loop evolution [14, 19] (Fig. 2).

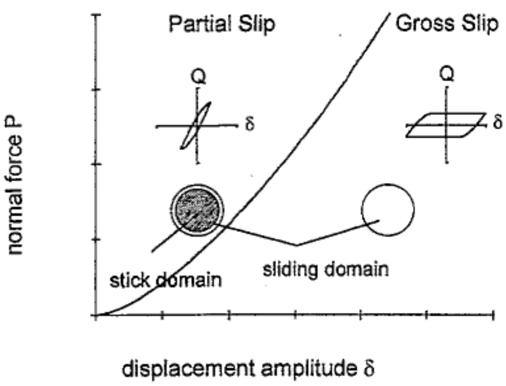


Figure 2: Sliding condition fretting map [17].

It is important to highlight that the Mindlin [13, 14] approach has been utilized until today to investigate the behavior of material (considering simplified test geometries); in this work this approach is extended to the components, that is splined couplings with crowned profile (the spline coupling teeth geometry has been considered as curvature radii).
Utilizing Mindlin's equations a fretting map for splined couplings used in experimental tests has been obtained (Fig. 3).

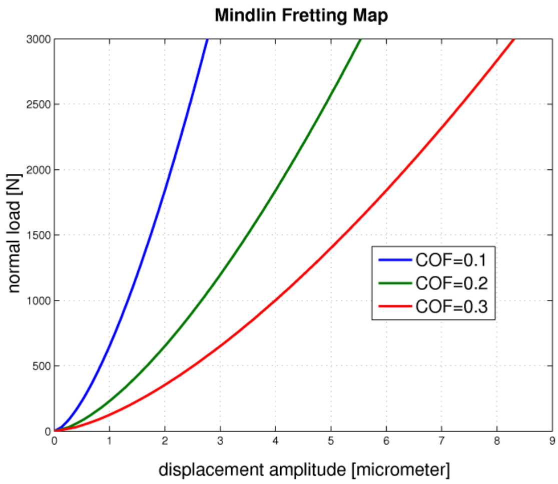


Figure 3: Spline coupling fretting map for different coefficient of friction values.

EXPERIMENTAL SET UP AND METHODOLOGY

A new test bench for splined couplings has been designed and realized [20] to analyze the fretting regime.
The main feature of the test bench is to apply and to monitor a specific angular misalignment between shaft and hub, so reproducing the real operating conditions of the component; the test bench allows a maximum inclination of 10' obtained by progressive increments of 0.5'.
Using some kinematic equations it is possible to determine the displacement and then the sliding that the points in contact between the two opposite surface of the specimen teeth may accomplish during a complete rotation. Tab. 1 shows the correlation between misalignment and sliding of the contact area during a test.

Misalignment [']	Sliding [µm]
1	4.8
5	24
10	48

Table 1: Values of sliding of the contact area during a test on the test bench.

Thanks to this new test bench it is possible to monitor a lot of experimental data (debris present in the oil, specimen temperature and strain, speed rotation, torque, etc.).
The test bench type used in this work has a mechanical power recirculation scheme, since the external power to be applied offsets only the power dissipated in friction [15].
A forced lubrication system is present and it reproduces the operating lubrication conditions of splined couplings. It is provided a heating system for the oil so that it can lead to a maximum temperature of 60 ° C.
Splined couplings specimens are steel made (42CrMo4) nitrogen-hardened; they have crowned tooth profile and the main characteristics are: 26 teeth, 1.27 mm modulus, 30° pressure angle, 200 mm crowing radius and 12 mm face width.
Once obtained the fretting map for a specimen, calculated on the basis of both geometrical (curvature radii) and physical parameters (mechanical property of material, coefficient of friction and normal force), it is possible to set up dedicated test conditions to realize the corresponding fretting regime.

In this work has been considered two value of coefficient of friction; one equal to 0.1 corresponding at steel versus steel with a particular type of lubricant used in aerospace application, the second value is equal to 0.3 referreding to steel versus steel without lubrication.
By observing Fig. 4, it is simple to note that the value of sliding, considering a COF=0.1 and a normal load under 1630.71 N (equal to have a 700 Nm of torque), is near to 1.9 μm.
On the other hand, Fig. 5 shows that with a COF equal to 0.3 the limit value of the sliding for achieving fretting fatigue or fretting wear phenomena (considering a force of 1630.71 N) is near 5.9 to μm.
Comparing Tab. 1 and Fig. 5-6, it is possible to observe that to obtain fretting fatigue phenomenon it has to be imposed a 1' misalignment and the test may be performed without lubrication; on the contrary for achieving fretting wear phenomenon it is possible to impose a generic value of misalignment (major or equal to 1'), but the lubrication may be activated.

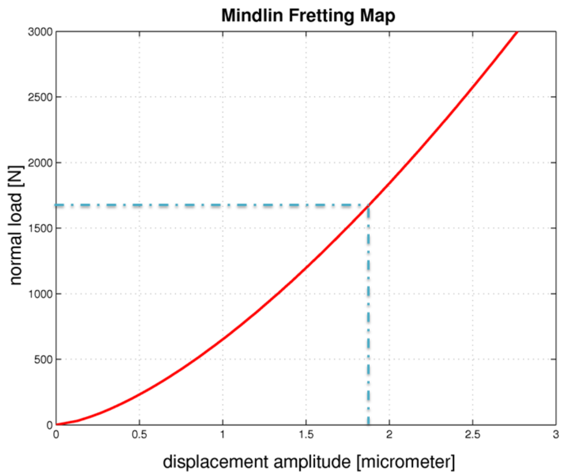


Figure 4: Fretting Map using a COF equal to 0.1.

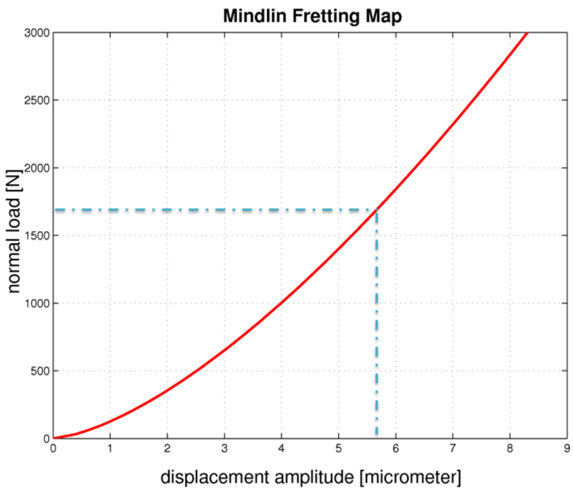


Figure 5: Fretting map using a COF equal to 0.3

Once established the sliding entity as a function of the torque value to reproduce different fretting situations, two particular tests have been carried out.
Tab. 2 resumes the working parameters related to the preliminary tests.
As can be seen, to investigate the kind of fretting phenomena, all tests have been performed with the same loading value (700Nm torque), the same spline coupling speed (1500rpm) and the same duration 10M cycles .

Test	Torque [Nm]	Speed [rpm]	Misalign. [']	Lubr.	N° of cycles
MB1	700	1500	1	no	10M
MB2	700	1500	10	Yes	10M

Table 2: Tests parameters.

RESULT AND DISCUSSION

Once the two tests have been over, the specimen surface has been analyzed in order to identify which kind of fretting damage has been appeared.
Fig. 6-7 shows the specimen before and after the test with 10 ' misalignment and with lubrication activation; from the analysis of this image it is possible to observe that no wear phenomena is present.

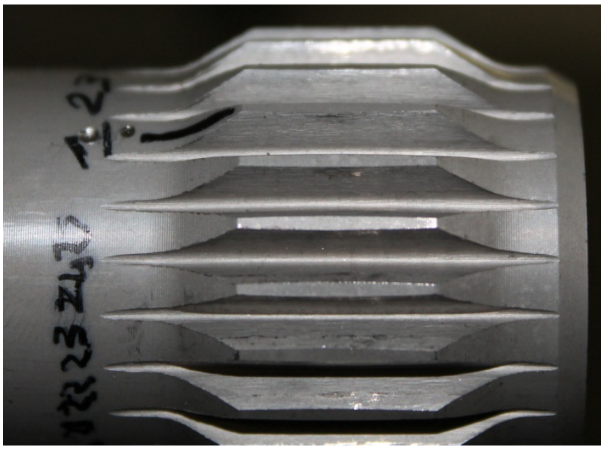


Figure 6: Face weight of the specimen MB2 before the test.

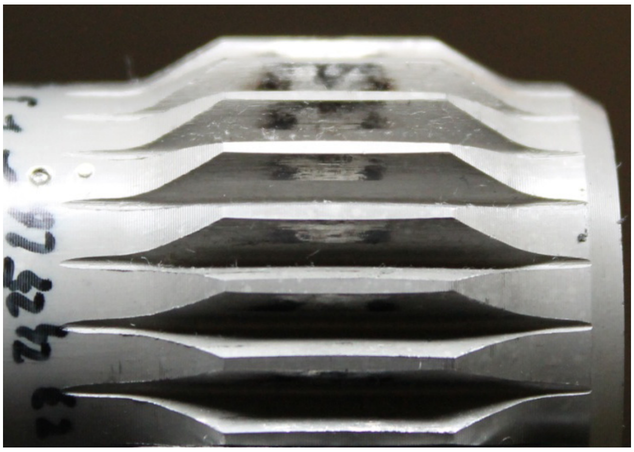


Figure 7: Face weight of the specimen MB2 after the test.

On the contrary, Fig. 7 shows wear area; in particular, the upper part of the tooth is worn.
This fact is probably due to a profile error causing the translation of the contact area on the upper part of the face width.
The wear zone has an elliptic form, with the central part more damaged that the boundary one.

The black zones near the ellipse boundary are the amalgamation of debris due to the sliding of the contact area during a complete rotation of the spline coupling.
On the other hand, by observing the teeth surface of the specimen used in test MB1 (Fig. 8-9), it is possible to note that on the surface is present, at the same time, a wear zone (in Fig., the darker zone) and a beginning of crack (in Fig., the white line).

Figure 8: Face weight of the specimen MB1 after the test (tooth 23).

Figure 9: Face weight of the specimen MB1 after the test (tooth 19).

The crack creation is probably due a very little angular misalignment (1') in test MB1 and consequently the whole test has been performed in the partial slip zone on the fretting map. As expected, the crack is located at the border of the wear area, where it is the edge between the stick zone and the slip one.

CONCLUSIONS

In the present paper different fretting phenomena have been reproduced and analyzed.
Different tests have been done and they are compared each other.
A significant difference was identified on the surface of specimen; the first test emphasized a fatigue damage and in the second test a wear phenomena has been achieved.
A good agreement has been observed between the experimental results of the two different fretting phenomena (fatigue and wear) and the analytical relationships.
Also a good result has been obtained by analyzing the fretting map obtained using the Mindlin's theory.
Finally, it may be conclude that by using an appropriate fretting map in relation on the surface curvature in contact, it is possible to preview the component (in this case a spline coupling) behaviour already in the design phase from the fretting point of view.

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