29th Nordic Seminar on Computational Mechanics
NSCM-29
R. Larsson (Ed.)
2016

MODELING NON-COULOMB FRICTION UNDER FRETTING CONDITIONS

NSCM-29

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Key words: Fretting, non-Coulomb friction, modelling.

Summary. Experiments have shown so-called non-Coulomb friction. In this study the non-Coulomb friction is modelled and simulated using FEM and a home-built subroutine. The non-Coulomb friction effect was successfully reproduced allowing detailed analysis fretting contact under non-Coulomb friction conditions.

1 INTRODUCTION

Fretting occurs when contacting surfaces are under short-amplitude reciprocating sliding motion, leading to fretting wear and fretting fatigue. Furthermore, fretting has been described as being efficient in producing small surface cracks and may causing surface degradation such as material transfer and fretting-induced increase in surface roughness. Fretting can produce high tangential tractions, which in combination with its surface degradation effects, may accelerate fatigue, which is the phenomenon known as fretting fatigue.[1]

In ideal conditions, the tangential force remains at a constant value during sliding. Therefore, an ideal fretting loops, i.e. tangential force vs displacement curve, should be rectangular or parallelogram with horizontal gross sliding parts[1]. However, many authors have reported so-called non-Coulomb friction, where the tangential force increases during the gross sliding phase leading to 'hook'-shaped fretting loops (Fig.1). The source for such non-Coulomb behaviour has been suggested to be tangential fretting scar interactions[2-4]. Mulvihill et al showed that a curved fretting loop can be reproduced with 'inclined sliding model', representing tangentially interlocked protrusions and depressions, while retaining a constant coefficient of friction[5]. Hintikka et al studied non-Coulomb friction further[6,7] and demonstrated that non-Coulomb friction occurred simultaneously with cyclic normal displacements, validating the inclined sliding explanation[8].

Contact modelling is typically based on idealized assumptions of true contact geometry and frictional behaviour. For example, classic Coulomb friction model is used frequently both in academia and in industries; although recent experimental findings show that such idealizations have limitations. In this study experimentally observed non-Coulomb frictional behaviour is simplified and modelled using commercial finite element software, Abaqus, using the FRIC-subroutine.

2 EXPERIMENTAL OBSERVATIONS

Fretting measurements have been done using sphere-on-plane fretting apparatus, with aluminium bronze vs quenched and tempered steel showed so-called non-Coulomb friction[6]. In non-Coulomb friction the frictional resistance against motion increases drastically when the fretting movement approaches its extreme positions as illustrated in Fig. 1. Experiments made using different sliding amplitudes have shown that the shape of the fretting loop is dependent on the displacement amplitude. By normalizing the displacement by its amplitude the fretting loops have roughly the same shape (Fig. 1). Based on latest non-Coulomb friction studies it is known that the non-Coulomb friction originates form tangential fretting scar interactions. Therefore, the non-Coulomb increase in the friction force is dependent on the sliding rather than displacement amplitude.

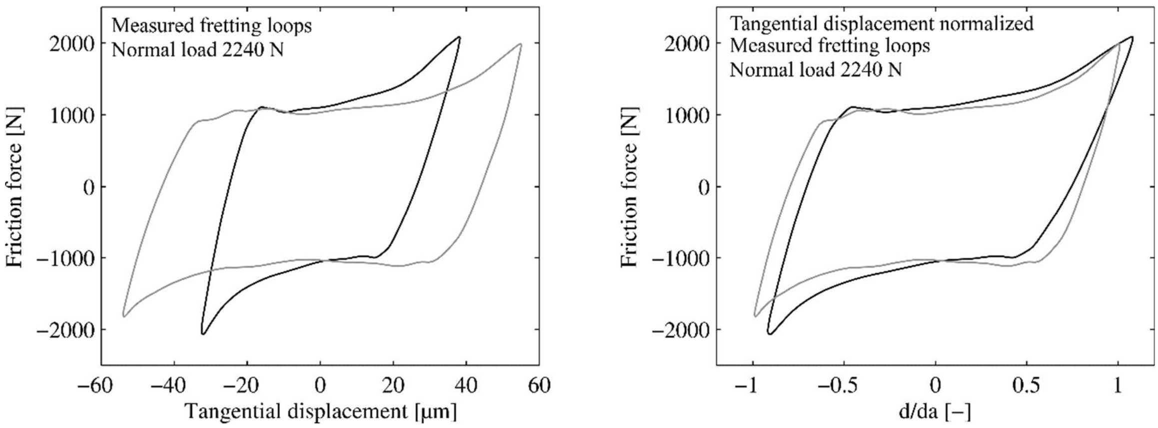

Figure 1 – Measured non-Coulomb fretting loops

3 SUBROUTINE

In order to model fretting induced friction properly, the non-Coulomb friction needs to be included. However, this is impossible to do using existing methods. In this study the modelling is done using Abaqus and the non-Coulomb friction is included by using its FRIC-subroutine, based on penalty friction formulation. FRIC subroutine calculates the tangential traction for each node separately. Otherwise, the FIRC-subroutine follows the penalty friction formulation as described in the Abaqus manual.

The total coefficient of friction COF is assumed to compose of two parts. The ideal coulomb part COF_I and non-Coulomb part COF_{NC}. Based on experimental observations the non-

Coulomb COF_{NC} is assumed to increase approximately exponentially as a function of slip per slip amplitude (Eq.1). In which power it occurs precisely, is not considered important at this stage, and basically any equation could be used. In the simulation of this study w = 2 and COF_{NC0} = 0.5, and it stands for the maximum of the non-Coulomb friction component, and COF_I = 1.0

$$COF_{NC} = COF_{NC0} \times |u/u_a|^w \tag{1}$$

The major challenge in modelling the COF_{NC} as a function of as shown in Eq.1 is the fact that the sliding amplitude is unknown beforehand and each node will have unique value for it. Hence, the sliding amplitude needs to be determined in the FRIC-subroutine by calculating it from the results as they are obtained during the running simulation. Of course this means that the subroutine stabilizes to steady state only after few fretting load cycles, which needs to be taken into account in the simulations. The sliding amplitude was determined by defining a vector, which length is monitored in each calculation increment. Once the vector length starts to reduce, the increment is labelled as point of sliding reversal (sr1), and new length vector initiated from that point. Once the second vector achieves its maximum length the second point of sliding reversal is obtained (sr2). The sliding amplitude and the origin of slip can be calculated from the distances between the two latest points of sliding reversal (sr_{i-1} and sr_i). The subroutine updated points of sliding reversals continuously (sr3, sr4…sr_i). In case of to and fro movement the locations of sliding reversal are obtained precisely; however, this approach allows sliding in both directions, albeit if the sliding path is too arbitrary it is possible that points of sliding reversals are not obtained correctly. A minimum value for sliding amplitude was given, before non-Coulomb friction calculations commenced in order to improve convergence. The method for defining sliding amplitude is demonstrated in Fig. 2.

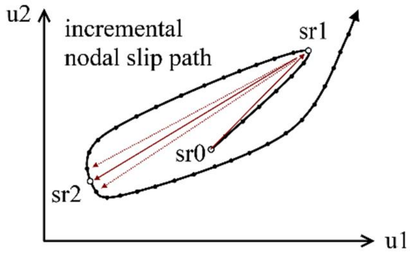

Figure 2 – Determination of sliding amplitude and points of slip reversal by measuring vector lengths

4 SIMULATION RESULTS

A sphere-on-plane contact was modelled in 3D and fretting load cycles were simulated using a number of different displacement amplitudes. Each displacement amplitude case was fretted for 10 load cycles ensuring that model achieved steady-state. Resulting fretting loops are shown in Fig.3, showing the overall reaction forces and tangential displacements. Basically, the transition from partial slip to gross sliding is reproduced reasonably accurately using the developed non-Coulomb friction model. The partial slip and transition to gross sliding was studied because the non-Coulomb effect is difficult to separate from the experimental data, which is largely defined by the compliance of the sphere-on-plane contact. However, by including the non-Coulomb friction such effects can by investigated using FEM.

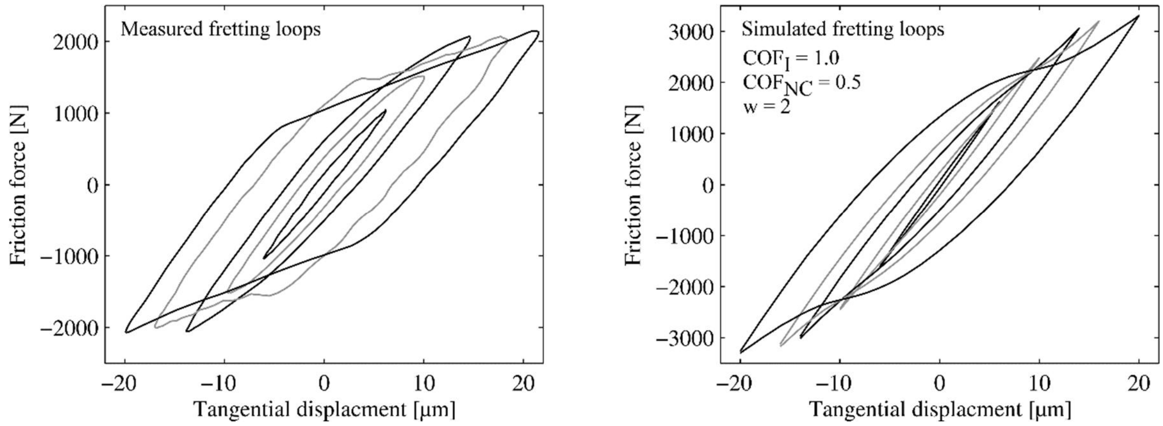

Figure 3 – Measured and simulated fretting loops with 2240 N normal load

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