164 Interdependence of friction, wear and noise: A review

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Phenomena of friction, wear and their interrelated noise in mechanical contacts are treated as one of the complex topics in tribomechanics when one has to define them mathematically in a collective manner. Efforts have been made to describe these phenomena separately with different approaches. However, the true analytics of these phenomena still requires comprehensive theory to define their interdependencies. To highlight the gaps in the existing literature, a review on the existing efforts is provided in this paper. The existing friction and wear models and their correlation with the emitted noise are extensively covered and critically analyzed. However, the review starts by detailing the past research related to the fundamentals of tribomechanics such as friction and wear at the asperitical level and hence allow a reader to comprehend the origin of the phenomena. Later, the review is explained under different sub-sections such as the relation of friction noise and surface roughness, friction induced squeal noise, friction noise and wear, numerical approaches in wear quantification and alternative of coulombs law of friction. The sequence of the sections is chosen to elaborate the microscopic attributes of tribomechanics in the start and later discussed the macroscopic wear behavior. Potential future directions of research are also detailed in the conclusion.

The fundamentals of friction at asperitical level are necessary in order to comprehend the more advanced friction models and this is introduced in section 2. Friction noise can be experimentally correlated to surface roughness and this is shown in section 3. The most common experimental setup to study friction is pin-on-disk experiments but there have been several numerical models to study rubbing noise as well. As for squeal noise, there have been numerical and experimental models that study them as well as shown in section 4. More in-depth experimental models correlate the wear volume to the sound pressure levels, and this is shown in section 5. Wear has also been studied numerically, as shown in section 6. However, sound pressure levels are not accounted for. Most of those models use Coulomb's friction model or Archard's wear model. There are more advanced models available which are in fact rarely used (most notably, physics-based models). Alternatives and enhancements to Coulomb's friction model can be divided into two categories. Empirical models and physics-based models. Those are detailed in section 7. Finally, the research gap is highlighted in section 8.

There are several techniques that can be used to investigate wear. Those normally include laboratory testing and exact operating conditions must be reproduced for the wear measurements to be accurate [1]. This can be troublesome when operating large machineries with several components under wear. Similarly, several models have been developed to account for friction and its relationship with wear [2]. Acoustic emissions caused by friction have also been extensively studied [3]. Most of the work done was experimental and the models rely heavily on empirical parameters. It can also be seen that a lot of the friction models are just refinements of the Coulomb model of friction [4]. As for the wear, Archard's model remains widely used in engineering, although several other wear models are developed, most remain empirical and based on experimental evidence [5]. Analytical work on friction and wear remains scarce. Another area of concern for researchers include the noise emitted by components under friction. This is most commonly seen in the automotive industry where minimizing the squeal noise of brake systems is regarded as very important for customer satisfaction [6]. Both experimental and analytical techniques are used such as simulation and modelling of brakes in a CAD software. Those techniques can also be used regarding wear caused by friction and this is also significant to the automotive industry

From a theoretical point of view, several friction models and wear models were developed separately. However, in all those cases, the acoustic emissions were not included in the purpose. The friction models that were developed as alternatives to Coulomb's model can be divided into two categories. They are either generally empirical models or physics-based models. Empirical models are based on experimental evidence. They rely on defined parameters that are fit to match the conditions for which the model is developed. This allows for an accurate model restricted to the exact purpose it was developed for even if the underlying science is not understood. Physics based models are general models that are created using general physics knowledge and thus can be applied everywhere. It is shown in this review that empirical models are still the model of choice in most friction problems and physics-based models are much less used. This is because they are still poorly understood, and their uses are still debatable. For example, De Moerlooze's model [7] is a dry friction model that agrees with experimental results from a qualitative point of view, however, it still falls short as it does not include asperity wear or lubrication. The EPB model [8] also presents many disadvantages. It is notably more demanding in terms of computational power (although with the increase in available technology, this problem can be diminished). Furthermore, the EPB model is unable to account for micro-displacements. The EPB model does need surface roughness measurements before it can be applied. This means that the surface roughness must be measured, the surface heights data must be processed in order to describe the asperity-level geometry and the height distribution. Another major problem (that is not exclusive to the EPB model) is that it does not take the evolution of the micromechanics surfaces into question. As the surface roughness changes, the EPB model's predictions will no longer be accurate. This ties in to the fact that those models do not include wear. However, no other experimental parameters are required provided that the material properties (Young's modulus, Poisson's ratio and yield strength / hardness) are known. The EPB model is also highly dependent on the contact conditions. It is applicable for highly-adhesive contacts at asperity scales. However, it is not applicable if the contacts have low adhesion. Empirical models are still the most widely used models in order to study friction-induced acoustic emissions. Furthermore, models studying noise and wear using lubrication are also not comprehensive.

The wear models are similar in that they are all empirical and have been created to suit a particular engineering application. Still, the most widely used wear model to this date is Archard's model. In the case of the study of frictional noise due to wear, Archard's model is the one most widely used. Its assumptions are relatively simple. The wear is proportional to the path of friction, it is also proportional to the friction work force and finally, it is determined by the physical parameters of the process and the mechanical properties of the material. However, such model presents a lot of disadvantages that will impact its accuracy. This is due to a lack of methods to suitably estimate the wear coefficient needed for the model. The different combinations of materials, modes of operations, environments, etc., often leads to a discrepancy between the experimental results and those obtained by the calculations. Other limitations of Archard's wear model is that Archard's law is only applicable for rough surfaces (plastically deformed asperities). It is not applicable for softer surfaces like polymers (which have elastically deforming asperities). It can also be added that Archard's law does not consider material evolution. Materials that initially deform elastically, may start to deform plastically as the contact area and the subsurface hardness changes. More advanced analytical wear models have been developed. However, they are mainly focused on the adhesive wear mechanism and do not take friction noise into account. In all those models, the Hertzian contact laws are used, although they are modified to some extent to account for the specific application at hand (such as including the effect of adhesion). Furthermore, all the studies relating wear and frictional noise have been experimental. Numerical studies of wear do not take frictional noise into account. The same can be said with regards to friction models and noise. All studies correlating friction (be it surface roughness or friction coefficient) have been experimental, using Coulomb's law. Alternative and more advanced models, such as physics-based models have not been used in regard to friction noise. Analytical studies regarding friction noise do not take wear into account. This means that there is no general analytical model that combines friction, wear and acoustic emissions in a single model, suitable for a wide range of engineering applications as all present models are empirical and are thus only suited to the specific application for which they were modelled. A single analytical model including friction noise, friction coefficient, surface roughness and wear volume could be a significant contribution to the existing literature.

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