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DISCUSSION

K. M. Skreiner[3]

The authors are to be congratulated for publishing their experimental and analytical work on the dynamic forces which arise due to clearances in the pin joints of linkage mechanisms. Their results promise to provide much-needed information for the designer of high-speed mechanisms in industry. It is hoped ultimately, from an understanding of the fundamental phenomena, that simple design procedures may be formulated. With this aim in mind, I would very much like to encourage continued activity in this field.

By employing both experimental and analytical approaches in this field, the authors have effectively closed the loop and have answered many questions in a most satisfactory manner. Their analytical model of the clearance-joint dynamics has been experimentally verified and, consequently, this can then be used in analytical design studies.

It may be of some interest to offer in this discussion some of our related experience in the design and the dynamics of mechanisms. This experience, combined with a good deal of inspired hunchwork, would agree with many of the authors' observations regarding the effects of friction, flexibility, clearances, and stiffness of the links and their joints on the dynamics of the mechanisms. Considerable work has been done to support the design of circuit breaker mechanisms and although not all of this has been published, some relevant papers [14-17][4] are given later. The large mechanisms transmit forces of hundreds of pounds through distances up to 30 ft with mechanism strokes up to 12 in. in operating times as short as 0.010 s or even less.

The mode of operation of such a mechanism is purely transient, as distinct from the cyclical or steady-state type of motion found in many mechanisms. Work has been done on measuring the friction of different bearing materials used in pin joints. In some cases, there is a stabilizing effect and the friction decreases with increasing unit loading. Compound materials, such as textolite or other fiber-reinforced materials, are often used as sleeve inserts in journal bearings. These have excellent load-carrying abilities, with low friction. Good control of impact forces is achieved by the relatively lower material stiffness compared to that of the parent links. Excessive clearances in pin joints, in addition to the reasons given in the paper, are undesirable because they tend to decrease the speed of force transmission through the mechanism.

The impacts in pin joints are not unrelated to the impacts of electrical contacts. This is a very important field in the design of electrical circuit breakers, since it has been shown that electrical performance is closely related to the mechanical system which controls the device. A glimpse into the nature of the impact forces in pin joints may be obtained by regarding the performance of electrical contacts. It is well known that the stiffness of the contact-pair interface is most important in their dynamics together with other factors, such as the relative approach velocity and their mass. The motion of electrical contacts is characterized by a series of short duration bouncing which is highly undesirable. The period of a typical bounce is of the order of a fraction of 1 ms up to 1–2 ms as an upper bound. This indicates that under some conditions, similar short-duration bouncing occurs in the pin joints of mechanisms. One question arises in regard to the selection of 100 Hz as the upper limit of the experiments reported by the authors. In view of the typical operating times cited previously, it would appear that data up to 1000 Hz and even higher would be of considerable value in this particular field. In addition, there arises the possibility of a resonance type of action as the frequency of the driving force approaches the frequency given by the mass/stiffness properties of a pin joint. This is not explored in the paper where frequencies of 4000–10,000 Hz are computed for the prototype pin joint.

Any comments the authors have on my points would be most welcome. In conclusion, again, I would like to congratulate them on a fine piece of work.

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Authors' Closure

The authors sincerely appreciate Dr. Skreiner's generous comments and would be most interested in learning more about the results of the unpublished studies performed at General Electric. In regard to the question concerning the 100-Hz frequency limitation, this upper limit was only applied to the fundamental frequency of the system and corresponds to a 6000-rpm machine speed. Such a speed is relatively high for a large class of machinery. The bandwidth of the measurements made was at least 20,000 Hz and thus the transient response within the connection should be adequately represented by the data presented and, in fact, these high frequencies were observed in the results as the impacts within the connection excited the high frequency modes of the system. The use of driving frequencies approaching the pin-joint natural frequencies of 4000–10,000 Hz (240,000–600,000 rpm) was not investigated because they were not considered relevant to the type of system under consideration. The authors would again like to thank Dr. Skreiner for his kind words.

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[4] Numbers in brackets designate References at end of Discussion.