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DISCUSSION

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In view of the size and importance of the computer/data processing equipment industry, it is surprising that so little has been published on something as fundamental to equipment reliability and life as wear.

The authors are to be commended for preparing this comprehensive review. It has long been needed, and their efforts will no doubt be widely appreciated.

When you look at the computer/data processing equipment industry and consider:

1. The many types of components utilized;
2. The large number of equipment manufacturers;
3. The dollar value of total sales;
4. The high percentage of sales spent on R&D;
5. The commercial age of this industry—about 25 years;

and then look at a comprehensive review with less than 100 references, it becomes obvious that practically no attention or importance has been placed on wear by this industry.

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This represents a significant unfulfilled potential. It means that equipment can be made which will be much more reliable, with much lower service and maintenance costs!

The changing physical nature of computer/data processing equipment implies a shift in their manufacturing cost structure towards greater relative importance for mechanical elements, and correspondingly, a lesser importance for electronics elements. This will give greater importance to the cost, reliability and lives of mechanical elements, and inevitably lead to greater attention to wear technology.

As a minor point, I take exception to the assertion that the wear of parts running against paper occurs by abrasion. In reference [80] I analyzed the published data to show that the magnitude of the wear rates observed were consistent with adhesive wear of metals being rubbed by polymers—it was unnecessary to propose abrasion arising from impurities in the paper. From a practical viewpoint, the only important fact is that wear against paper follows a linear wear law, and the empirical wear coefficient is relatively small.

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F. W. Dauer[7]

The authors are to be commended for their attempt to cover such a broad subject as Wear Problems in the Computer Industry, in a single conference paper. Of course one's first reaction is that the work is shallow, particularly dealing with bearings and magnetic recording. However, upon reviewing the references listed, it is obvious that a good "first start" has been made to direct the reader to additional works on the subject.

Wear Problems . . . are grouped into 6 subject areas. Because of the limitations of space in my Discussion I will only briefly comment on these, and add additional material where I feel its necessary.

Printers. Historically line printers have been around since the early 1950's. These printers commonly used paper, clutches and brakes, gears, bearings, springs, switches, and electro mechanical hammer drivers. Industry has historically explored the subject of wear by component evaluations during expensive testing programs. Little analytical work was done by industry until the 60's to determine what was actually taking place during impact printing. It has only been recently that the subject was well enough understood that attempts to design for minimum wear were attempted based primarily on analytical considerations. Papers on the analytics of impact printing have not been encouraged by the computer industry. This has been due to the extreme competitiveness of this particular sector of U. S. business. Another fact that has limited discussions among researchers in the field has been the unavailability of suitable instrumentation to measure the parameters of interest. Each instrumentation setup has been proprietary to the particular company. Almost nothing has been published to date on impact printer instrumentation. A recent work is [81].[8] On the subject of wear in printers, the only work I know of is the book by P. A. Engel (reference [12]), and resulting paper [82]. However I pointed out in my 1966 paper (reference [6]) that impact printing is highly nonlinear. Engel's work is concerned with linear theory, so much has to be done to extend the theory into the nonlinear range.

Recent works on impact printing not cited in this paper, are [83, 84, and 85]. As one can see the math models are far from being in agreement. The problem seems to be the media impacted; i.e., the paper. I have called for additional standards by the paper industry in the hope of resolving this problem (reference [1]).

Today impact printing theory is close to being finalized. However, the analysis must include nonlinearities if it is to be realistic. It is to be hoped that more will be published by reputable researchers so that math modelers have realistic data to base their theories on.

2. Magnetic Recording Technology. Disk and tape drives are widely used in the computer industry and wear is a problem at the read/write head recording media interface. Based on experience in the EDP peripheral field, the disk drive has probably the most complex frictional wear phenomena of all peripheral devices. The reason is that the landing and take-off of the read/write heads is irregular and unpredictable.

Disk Units. The take-off of the read/write heads involves multiple impacts with the asperities of the disk surface before a hydrodynamic air film develops which allows the head to become stable and separate from the surface. We know of no published mathematical model to describe this take-off or landing of the head. The landing is essentially the opposite of take-off. Wear results from impact coupled with sliding friction. In order to reduce the wear on the heads and disk, after the introduction of Winchester technology, disk manufacturers started using lubricated disks. Typically the lubricants used for the disk surface were highly stable synthetic compounds. They are propriety to the disk manufacturers, and a user is forced to either accept or reject the disk based on in-house wear tests.

The thickness of the lubricant is important, because too little affords inadequate protection, and too much results in the "jo-block" effect. For the uninitiated this effect is similar to surface adhesion; i.e., it does not allow the heads to be separated from the disk surface. In actual practice, if the jo-block effect is present, the heads break off from their supporting members.

One in-house test developed by industry is an accelerated wear test to check the adequacy of disk lubrication. The test is essentially to load a 2 RMS, .9525 cm diameter, ceramic (Al_2O_3) ball on the disk at 70 gm force, 200 RPM and 17.78 cm radius, and measure the torque generated (from which a coefficient of friction change can be calculated). Typical values are in the neighborhood of $.1 \rightarrow .15$; the lower value is for the earlier time. Accelerated test time is 10 minutes, which corresponds to about two weeks life testing of the actual hardware.

Most manufacturers of disk drives specify 10,000 landing/take-off cycles before any degradation of mechanical or electrical parameters. Deviation from 10 percent is considered abnormal.

Tape Units. In tape drives, "head wear is one of the prevalent and expensive component problems associated with abrasivity. The useful life of a magnetic head bears a direct relationship to many interrelated factors such as type of head, transport type, tape velocity, tolerances, and abrasivity of tape. This life may range from 100 hours to several thousand hours, with the final limitation being imposed by the abrasive characteristics of the magnetic tape that contacts the head. The cost of head replacement alone is significant enough to warrant user concern. When one considers the other factors, such as constantly changing head characteristics and the possibility of damaging tapes and subsequent loss of data due to changing head conditions, it is essential that the user be made aware of the abrasion characteristics of magnetic computer tapes, and their impact on maintenance and replacement of component parts. A similar rationale applies to capstans, tape guides, and other path components [86].

Today Al_2O_3 is used for the tape guide flanges, and the guide barrels are nonmagnetic stainless steel. The capstan requires special design—it must have low inertia and high friction. Special coatings are used over base metal to provide the friction required. The read/write head is a special problem. Du Pont Tribaloy T-800 is used to coat some currently available heads. The tape path has glass beaded tape at critical friction points. All of these "solutions" to the wear problem must be continuously upgraded as higher tape speeds are required.

In most tape drives today, after about $20{,}000 \rightarrow 40{,}000$ short section oscillations of the tape past the head, the electrical signals degenerate enough to give a permanent read error. Constant running does not wear out a head as much as start/stop—this is because of air film decay. Head life data are not published in advertising literature, but is usually listed in the machine specifications. Tape wear of the head

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[8] Numbers 81–91—brackets designate Additional References at end of discussion.

does two things: (1) it reduces the pole tip, and (2) it makes the tape fly higher. The ideal tape/head interface is an air bearing. If the tape/head distance gets too large then one gets poor read/write performance; if too small one gets head wear. So, as one can see, the problem of head design to reduce wear and enhance signal performance is common to the industry. Hence, special coatings, geometry changes and tape lubrication have been used to date to enhance performance. Another problem in tape drives is head contamination. Improper correcting of this problem can increase wear—so there maybe a tradeoff. Air is one of the most effective lubricants. However, in a typical tape drive the tape alternately scrapes the head and is hydrodynamically supported (tape flies). The thickness of the air film and its stability are major research problems. A typical value is 254 microcentimers!

Loose oxide particles on the tape add to the contamination problem. A cleaner block is used to take them off. This, of course, increases wear of the tape since most cleaner blocks have sharp knife edges [87].

3. **Bearings and Lubricants.** While both gas bearings and contact bearings are used in computers and peripherals, the major wear problems are associated with contact bearings of the rolling variety. Rolling contact bearings are used extensively in spindles, guides and ways and are often required to perform not only as low-friction, long-life contacts but also as precision positioning elements. Bearing performance problems can be grouped into two categories, (1) noise related problems and (2) positional accuracy related problems. The latter group is surely the most challenging to the designer. Noise problems include sources such as cage rattle and instability, grease popping and whine which are often non-functional (albeit annoyances), as well as the more troublesome noises such as those associated with seal drag and parasitic resonances within the bearing. While bearing noise is almost always an annoyance, particularly to a technician trained in the use of his calibrated ear to detect malfunction, it is often not indicative of a functional problem. The real challenge to designers and engineers is to "listen" to the audible signature of a bearing and be able to determine what it means. Real time spectrum analysis of both the airborn and structure borne noise is a tremendous listening aid. Lubricants play the preponderant role in rolling bearing wear. The lubricant selection must be made based on obtaining adequate asperity separation between balls and races. Greases are usually used rather than oils because of their high kinematic viscosity characteristic which allows a thicker, more tenacious lubricant film to be developed in the squeeze channel. Of the many greases currently available, the two-phase systems comprised of either a sodium or lithium soap and either a hydrocarbon or ester oil are preferred. A grease system which is easily channeled, is usable up to 200°F, and continues to exude the base oil into the ball path, is often selected for both periodic and oscillatory motion applications. Small amplitude, oscillatory motion is often required and presents a particularly difficult design problem. Here the ball/race speeds are too low to develop a good lubricant film thickness, and the turn-around accelerations impose large dynamic loads between the balls and cage which can result in cage spalling and ultimate wear failures. Ball skidding is also aggravated. Retention of the lubricant can also be a problem, particularly in cases where the bearing is in close proximity to the storage media (e.g. a spindle and a magnetic disk, or an idler bearing and magnetic tape). In these cases, it is wise to use seals (not shields) on the bearings, use a grease with high surface tension properties (not an oil) and minimize the amount of lubricant used in the bearing. Insofar as the bearings role in obtaining positional accuracy is concerned, spindle bearings and carriage bearings used in high-data density disk drives must often demonstrate less than 508 microcentimers of runout at the assembly level. Some current day requirements demand better than 127 microcentimeters position accuracy. To achieve this, the bearings must be near perfect (either ABEC class 7 or selected class 5) in their geometry. In addition, the designer must give special consideration to the mounting arrangement of the bearings, being careful to achieve maximum stiffness against overturning moments and to minimize anisoelastic moments. Race waviness and undulations also become important considerations. While many factors influence bearing wear, the role of the lubricant is paramount. A properly sized, adequately lubricated bearing which has not been damaged (i.e. brinelled) during assembly will provide many years of troublefree service [87].

4. **Gears.** All profiles and distances being perfect for a gear and pinion, the biggest problem in gear wear is the lubricant, surface finish and the materials used. If one has high loads the relative sliding results in a local temp rise, Bhushan [88–91] which will melt plastic gears and destroy the lubricant film.

Since the theory of good gear design is now well known, manufacturers of gears are concentrating on profile precision and metallurgy. It has been up to the users of these gears to choose lubricants, surface finishes and quality desired.

Today, timing belts have mostly replaced direct gear drives in the computer industry. Also D.C. servo motors have found increased application as gear transmission replacements.

5. **Paper.** Paper scuffs under wear conditions and the lint gets into bearings, gears, type, etc. Paper is very abrasive and hard. Everyone remembers a cut tongue or finger from opening or closing envelopes. In impact printers that use inked ribbons the paper dust combines with the ink to form an almost glue-type substance that gums up the type. Air gaps of some printer hammer solenoids have changed due to accumulated paper dust. In card handling equipment the card feeder rapidly wears due to paper movement and subsequent friction. The paper tractor pins on printers wear rapidly due to impact of the pins with the paper during feeding. Printer typewheels rapidly wear on the characters of greatest use. As far as I know no manufacturer of paper has come up with a product yet that has built in lubricity—perhaps this will be required in the future.

6. **Electrical Contacts.** Relative sliding of conventional electrical switches is necessary to get sufficient wiping action for good electrical contact. In low amperage applications most contacts today use gold, rhodium, palladium or Western Electric alloys in their designs. Cross bar switches seem to be popular in the computer industry. For non-sealed switches, typical life today is around 10,000,000 operations. For sealed switches 100,000,000 operations is typical. The costs of switches have decreased drastically over the years. Solid state switches are now replacing the conventional type in many computer applications. While research is still going on contact alloys and lubricating films, I feel that the solid state switch will eventually replace most conventional switches in computer applications.

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Authors' Closure

The authors are grateful to E. F. Finkin and F. W. Dauer for their thoughtful comments.

A few brief comments to the discussions are offered below.

Dauer, rightly, points to the nonlinear nature of impact printing. Such nonlinearities are foremost in the force-deformation relations. However, the wear process resulting from repeated print cycles can be either linear or nonlinear in terms of the print force and the cycle number. Reference [12] cites examples for both cases, depending on the impacted media.

As far as wear mechanisms involved in the wear by paper and ribbon, more on this subject is found in reference [37].

In response to Dauer's comments on electric contacts, it is noted that the paper explicitly specified connectors under *dry circuit* conditions (low voltages and low signals). The connectors of this group are characterized by relatively high contact forces and large wiping distances, because the operating voltage at the contacts remains below the *minimum arcing voltage* which depends on the contact materials.

Connectors are greatly different from switches in function, operational conditions and wear behavior. Most switches are sealed-in today in order to reduce wear or material loss due to arcing or glowing discharge.

The solid state switches mentioned by Dauer are definitely a significant advance in switch technology. However, they can only replace some conventional switches where voltages and currents are not too high. The solid state technology has not impacted the connector technology as yet, and may not affect it at all in the foreseeable future. The connector requires a physical separation of two parts when the electrical contact is unmade, for most frequently replacement of new parts is required.