RESEARCH NEEDS AND OPPORTUNITIES IN THE AREA OF INTERACTION OF FRICTION AND SYSTEM DYNAMICS

Report of the Workshop on the Interaction of Friction and System Dynamics held August 8-9, 1994 in Pittsburgh, PA

Sponsored by:
The National Science Foundation

Outline of the Report

November 27, 1995

PREAMBLE

A workshop was held on August 8-9, 1994 to investigate the importance to industry of the interaction of friction and system dynamics and to identify potential areas of research to ameliorate some of the problems such interactions can raise.

The primary issue at hand was how to characterize the interactive nature of friction and system dynamics. It was made clear in several of the presentations that the dynamic response of a mechanical system excited by friction also influences the nature of the friction force acting on it. In other words, friction force acting on mechanical systems is interactive with their responses. Such interaction should be considered to include all dynamic parameters, such as temperature, material properties, surface properties, etc.

The goals of the workshop were also poised to identify the major industries that are affected by this specific subset of friction-related problems and determine the progress-enabling areas that need more emphasis by researchers.

The workshop was attended by representatives of industry, academe, several government agencies and national laboratories. The presentations made reflected the current problems stemming from friction and system dynamics and summarized the state of the art in this field; agenda of the workshop is given in Appendix A. The steering committee and the attendees are listed in Appendices B and C, respectively.

ACKNOWLEDGMENTS

The steering committee would like to express its thanks to all of the speakers and participants of the workshop, in particular to Mr. Lou Ross, Chief Technical Officer and Vice Chairman of Ford Motor Company for his plenary presentation which underscored the vital importance to industry of the interaction of friction and system dynamics.

The sponsorship of NSF and the guidance provided by Dr. Jorn Larsen-Basse and Dr. Davendra Garg, the directors of Surface Engineering and Tribology and Dynamic Systems and control Programs, respectively are gratefully acknowledged.

Technical and staff support were provided by the ASME Center for Research and Technology Development and Carnegie Mellon University.

SUMMARY

This report documents the discussions and findings of a workshop on the interaction of friction and dynamics, an area of vital importance to mechanical design and operation of systems in which friction plays an important role. This area deserves special attention in light of the problems that are chronic to a host of manufacturing industries and products, such as brake systems for automotive and aircraft applications. Engineering solutions to such problems are generally developed by representing the frictional characteristics of a material or surface as a single number of parameter form that is independent of the overall dynamic system. The resulting solutions can be seriously misleading. Furthermore, friction measurements that ignore the vibration response of the test system often generally lack repeatability and can in other ways be misleading.

This report is not intended to cover all the research needs associated with a better understanding of friction. A report that documented an earlier workshop [1] addressed a number of such recommendations. The current focus is instead on the effects of system dynamics on friction forces and friction-induced dynamic response. An effort is made to put in proper context the many variables that influence friction.

Many specific examples are given later in the report in which the interaction of friction and system response are important. In addition, some baseline assessments are made of friction related issues, the solutions of which are deemed by researchers and engineers as critically important to a wide range of industrial applications.

One outcome of the workshop was the underscoring of both the need by industry for advancements in this area and of the breadth of complexities involved. The workshop also reinforced previous conclusions that the approaches to date on friction related problems vary considerably and lack the benefit of effective communication among researchers. This report concludes with a final recommendation to bring together noted experts in areas including tribology, continuum mechanics, dynamics, materials, and industrial applications to further identify specific research needs, the results of which will enable more accurate engineering predictions of the interactive nature of response and interface behavior.

I INTRODUCTION

The overall cost of friction related problems to American industry exceeds several billion dollars annually. Two major causes are unintended power dissipation and wear. A third cause relates to the coupled interaction of friction with system dynamics -- common examples of which include stick-slip, chatter, friction-induced vibration, and the fundamental issue of friction measurement repeatability. A highly visible example of this third cause is the inconsistent behavior of brake systems, commonly categorized as noise, vibration and harshness, which now costs the automotive industry hundreds of millions of dollars annually in warranty claims. Similar problems are common with aircraft brakes.

The traditional treatment of vibration problems in which friction forces are present is to represent the friction force as the product of the force normal to the friction surface and an empirical constant. Friction is thus represented as an external force on the system. This assumption is mathematically convenient and can yield solutions that reasonably represent physical systems under certain restricted situations, particularly when the influence of friction forces is weak. However, system dynamic response can sensibly alter friction forces, in which cases the representation of friction as an external force can lead to highly erroneous and misleading results. The primary issue is therefore how to characterize the interactive nature of friction and system dynamics. Considering the many parameters that are known to influence friction, such as rigid body oscillations, structure-borne waves, wear, heat and acoustic dissipation, contact stress distribution, and chemical reaction, and debris, materials, environment, lubricants, etc., clearly a comprehensive representation of friction-induced vibrating systems can be extremely complex.

II. BACKGROUND

Friction is ubiquitous in all mechanical systems with moving parts. In most cases friction is ancillary, and even detrimental, to the function of the system. In other cases, friction is the primary function. Accordingly, friction has been defined as a force that resists relative movement, as a dissipation mechanism, and less frequently as a mechanism of energy transfer. While the most common and earliest experiences with friction have been to minimize its resistance to relative motion, friction has also been used to advantage as a means to dissipate energy in friction dampers and brakes and to transfer energy in friction drives, clutches, belt-drives, etc.

Friction appears in the context of so many different applications and conditions that discussions about it should be application-specific. Friction between the head and hard disk of a computer operates under much different conditions than friction in aircraft brakes, for example. The conditions of the specific application also determine the mechanism of friction. For example, in cases where contact is very light, the resistance, dissipation, and energy transfer mechanisms rely on the interaction of the asperities. In cases where contact is very strong, as in brakes, the surfaces may undergo such extreme temperature and pressure changes that the interface experiences chemical reactions and the material properties of the mating objects change dramatically.

The changes a friction pair undergoes as a result of friction depend on numerous factors which have been traditionally considered under the topics of surface properties, material properties, normal load, temperature, and the like. As the complexities of system responses arising from friction increase, a more detailed understanding of factors influencing friction has become necessary. The complexity of friction is exacerbated by the interrelationship of the many factors that influence it. For example, nonflat surfaces develop hot spots which lead to wear, thus changing the surface friction characteristics.

An important aspect of friction is its interaction with the dynamics of the system of which it is a part. This is considered to be the underlying phenomenon in numerous industrial problems and applications outlined later in the report. The mutual influence of friction and the dynamic response of a system on each other might take several forms. For example, interface friction might induce elastic waves within the bodies in contact that modify the contact between them and, as a result, also modify the friction force. As another example, friction forces resulting from contacting surfaces with relative motion will always have some normal component, which correspondingly will alter the contact load and thus the character of the friction force. Lack of accounting for the dynamics of the system response in assessing the role of friction leads to incorrect conclusions.

In summary, because friction occurs under many different conditions, meaningful generalization is very limited. There are many interrelated factors influencing friction. Dynamic response of the system in which friction exists is an important one of them.

III. TECHNICAL NEEDS

The technical headings for research needs in friction-induced vibration and noise in mechanical systems are described by the primary functional references: friction devices, manufacturing processes, materials handling, friction-induced damping, and position control.

A. Friction Devices

Brakes and Clutches

High-frequency brake squeal is the major vibration-induced problem in brake technology today. This century-old problem is found in many transportation modes (including rail, aircraft and automotive) and in brake systems manufactured in all countries.

There is a strong need to develop engineering solutions that preclude brake squeal. A fundamental understanding of the physics of brake squeal is needed and could be dramatically advanced by development of a test facility that could consistently generate brake squeal on demand. The need for and technical advantage achieved in obtaining a solution to the fundamental and unresolved dynamic system problem of brake squeal would be very great indeed.

Roughness in brakes and clutches describes a state of self-excited, multimodal, nonlinear oscillation that is a problem second only to brake squeal. This problem area calls for attention to a comprehensive physical understanding of the clutch-brake-system environment that can be described analytically and verified within some range by experimental observation.

B. Manufacturing Processes

Chatter

Chatter in machine tools is self-excited, nonlinear oscillation of the machine tool, coupled to the workpiece and machine tool structure, typically found in turning and milling operations. The presence of chatter limits the cutting speed and cutting quality. Not only can it affect the part surface roughness and lay, but it can affect tool life. Chatter can be produced by the formation of built-up edges on the tool tip that leads to high friction forces (self-mated contact). Advance in modeling chatter suffers from a lack of reliable friction model that accounts for vibrations of the mating surfaces.

Vibration-Assisted Machining and Forming

Vibration of cutting tools and dies can be used to assist machining operations by altering the friction on the interface between tool and workpiece as in the vibration of planing knives in the peeling of wood.

In manufacturing, the friction on the interface between tool and workpiece will always provide a substantial limit on the performance of the process. Vibration is also a positive control for some processes, for example, cold drawing of wire while vibrating the die has been shown to be an effective method. There is a need to develop analytical models to describe the physical processes involved in the machining processes.

Vibration-Assisted Assembly

In the assembly of machine elements and manufactured components, especially automatically in robotic and servo-controlled systems, vibration can effectively improve alignments and influence interface-friction to assist the processes. Detailed models of the interactive process between vibration and friction between the contacting surfaces are necessary to enhance vibration-assisted assembly processes.

Friction in Positioning Systems

Friction in robotic and other positioning devices used in manufacturing and assembly of products limits automation. Accommodation of friction in control algorithms is complex, because of the nonlinear and indefinite behavior of friction. On the other hand, friction drives can be used in high-precision applications that require limited tractive force. The nonlinear behavior in positioning devices, particularly at low velocities, requires investigation effects of friction on system dynamics at low relative velocities.

C. Materials Handling

Web Handling

The transport of very flexible, two-dimensional, web-like sheets is common to many manufacturing processes, such as in textiles, paper, printing, coating, etc. For such purposes, friction forces are inherent to the web transfer. The web generally passes between rollers, and may slide over guide surfaces.

Handling of paper and other materials during printing or coating is complicated greatly when extremely high tolerances must be maintained such as with overlay of different colors.

Some printing machines and copiers also utilize friction to pass paper through the machine. The positioning of the paper and the rate of its passage are controlled by friction.

The precise positioning and transport of webs in a manner that prevents breakage, surface damage, wrinkling, and flutter while maintaining high speed production is the key objective of the research needed in this area.

Tape Transport

Magnetic tapes used to electronically store information experience friction problems that limit the technology. Tape guides, used to position the tape over the read-write head, are subject to wear and consequent loss of positioning accuracy. The guides can also cause tape edge damage. Friction at the head itself can also result in self-excited vibration of the tape and misregistration of the tape-to-head. Complete analysis and design guidelines require better description of the friction processes between tapes and guides.

Belts

Belt drives of different types rely on friction to transmit power. Their precision in positioning the pulleys and their wear are influenced by friction. Friction-induced vibration in belt systems often creates unwanted vibration.

All belts experience noise problems that can not be predicted accurately. It is a troublesome problem for the automotive and the computer industries, among others. The belt-friction-dynamics problem is a system problem requiring investigation and laboratory evaluation of the phenomena behind the dynamic responses of belts.

Synthetic Fibers

Synthetic fibers are handled at high speed during their manufacture and subsequent end production. In all cases, guiding of the fibers is a process controlled by dynamic-friction. The friction forces that develop during contact of thin-cross section fibers moving at high speeds require better models for more accurate description and design of the dynamics of fiber manufacturing processes.

D. Friction-Induced Damping

Frictional damping in mechanical systems is often necessary to functional success. However, the damping relied upon is now generally of indefinite character and unspecified magnitude. Correspondingly, there is inherent design uncertainty and limited optimization in such operations.

Fasteners and Assemblies

Junction fasteners, such as nails, screws, nuts, bolts, lock washers, and studs, rely on friction for functional integrity. Friction environments are known to loosen such fasteners, and engineering guidelines are highly empirical and not always reliable. A better physical understanding of the dependency of fastener functionality with friction is needed.

Junction assemblies connected by bolts, tack welds, etc., are known to be sources of frictional dissipation; they can be used to advantage in stabilizing dynamic systems and in minimizing vibration amplitudes. However, the micro slip dissipation mechanisms are only weakly understood, which limits the enabling utility of this mechanism in product design.

Friction Dampers

Friction dampers have many explicit and implicit product applications. Explicit examples would include damper rings in gears; implicit ones would include the above fasteners and turbine blades inserted into rim slots or discs. However, because the underlying mechanisms are not well understood, the full utility of friction dampers is only weakly exploited. A systematic study of friction dampers common to engineering design is needed -- an objective of which should be accurately quantified design guidelines.

E. Measurements

The complexities involved in the modeling of friction also manifest themselves in the measurement of quantities that are friction related. The continuous change of properties, such as temperature, surface roughness and many others, during a friction process, combined with the dynamic response of the measurement set-up, makes measurement of the resistive force and dissipation by friction very difficult. More well controlled and measured tests are needed that detect the full character of relative motion with respect to the controlled independent variables.

IV. BASELINE ASSESSMENT AND GAPS: PREDICTIVE FRICTION MODELS AND TEST METHODS

The fundamental technical needs outlined in the last section center on the reliable prediction of friction-induced responses. To date, there exist no generically valid friction models. Hence engineering designs are valid for only specific conditions for a specific application and the full domain parameters of acceptable performance are not accurately understood. The lack of applicability of predictive models also limits the validity of friction measurements to industrial applications.

The present dry friction models are inadequate to support contemporary product design strategies. There are also several issues with contemporary measurement and test methods that include:

- assignment of a single value for coefficient of friction for a given tribosystem, in the face of overwhelming evidence on the variation of friction with time.
- lack of repeatability of test data
- wide spectrum of test methods
- sub-scale to full-scale correlation limitations

As the consequence, there is strong, justified reluctance on the part of designers to rely on published data for design purposes. More reliable descriptions of friction are industry- and application-specific, and the largely intuitive parameters generally include:

- asperity density and size
- relative surface speed
- surface temperature and heat flux
- history, particularly prior wear
- geometry
- contact loads
- non-steady effects including inertia forces

For each of these parameters, there are a host of measurement issues. Current test strategies are inadequeate for measuring and controlling these parameters, however.

At the core of the current issues is whether or not friction is an intrinsic material property that can be isolated by measurements. Measurements of the relative influences of surface chemistry, material properties, or system dynamics, to achieve a desired system response, awaits further developments in the measurement of friction.

V. GO-FORWARD HYPOTHESIS AND RECOMMENDED GOALS

Hypothesis elements

• The value of contemporary models is not advancing and falls short of current design requirements

• There are time-dependent variables that must be precisely measured and correlated with friction; these include speed, load, area, geometry, combined roughness, and ambient medium.

There is a need to understand what material elements and events are of first-order relevance, e.g., material empirical constants such as elastic modulus, Poisson's ratio, yield strengths, etc. With these variables quantified and correlated, there is a chance to advance to a new paradigm of friction characterization. Further, an evolutionary approach is essential to meeting the predictive design strategies necessary to meeting cost, cycle time, quality, and new opportunities for design inventions and innovations.

Recommended Goals

• Exploit current advanced models to the limits of their applicability. This requires test strategies that place adequate control and measurement emphasis on intuitive parameters outlined above.

• Determine models for friction that are sufficient for engineering use in predicting dynamic response of engineering systems.

• Develop friction maps that correlate friction response as functions of independent variables.

• Conduct rigorously controlled tests that require clear understanding of the independent variables and their ranges of applicability.

• Develop friction models that predict friction instabilities that are non-system specific.

• Conduct exploratory research to define knowledge necessary for advanced understanding and more rigorous predictive models.

• Develop better quantification of the true area of contact.

Beyond the emphasis on understanding of friction, we must develop design strategies that de-sensitize systems to wide variations in friction behavior, such as those that are known to exist in brakes, for example.

VI. FINAL RECOMMENDATION

Even the definition of friction seems to be application- and, sometimes, discipline-specific. It is variably referred to as a resistive force or dissipater of energy while it also has the role of transferring mechanical energy as in friction drives. The factors that define friction are traditionally identified from the perspective of the specialist, i.e., chemist, physicist, material scientist, or mechanical engineer. Each of these perspectives, respectively, addresses a different length scale, and even time scale, with increasing order of magnitude from nano to engineering scales. The organizing committee finds it essential that a limited number of representatives from each of the disciplines addressing friction-related issues, both the researchers and the industrial users of these research results, should be brought together for a workshop with the specific focus of defining a plan to integrate existing knowledge and future research among research and applications. The organizing committee feels strongly that it is essential to strengthen the communication and coordination among the research communities in order to make significant advances in this field that would bring out usable results for industry in the near future.

Therefore, the final recommendation of this report is to bring together a modest number of experts from areas such as tribology, physics, chemistry, continuum mechanics, dynamics and vibrations, and materials to focus on specific research needs that will assist industry to predict the interactive nature of system response and interface behavior.

VII. REFERENCE

1. Research Needs and Opportunities in Friction, ASME Publication CRTD-Vol.28, 1994.

APPENDIX A - Agenda

NSF/ASME Workshop on Research Needs
in Friction/Vibration Interaction
Monday, August 8, 1994
Holiday Inn - University Center, 100 Lytton Avenue, Pittsburgh, Pennsylvania

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Agenda

7:00 - 8:30 **Registration** (also Sunday evening 7:00-9:00 pm)

8:00 - 8:30 **Continental Breakfast**

8:30 - 9:00 **Opening Remarks**
S. Director, Dean, CIT
J. Larsen-Basse, NSF

9:00 - 9:30 ***Interaction of Friction and Vibrations; An Overview***
A. Akay, Carnegie Mellon University

9:30 - 10:00 ***The Importance of Friction to the Auto Industry***
Lou Ross, Vice Chairman & Chief Technical Officer
Ford Motor Company

10:00 - 10:15 **Break**

10:15 - 12:00 **Industry Perspective**

Friction-Induced Brake Noise and Vibration
S. Rhee, AlliedSignal Corporation
Automotive Brake Noise & Vibration; Friction Materials
M. Weintraub, Ford Motor Company
Application Needs and R & D in Friction-Induced Vibrations
R. Rorrer, The Gates Rubber Company
Measurement Systems & Friction-Induced Noise and Vibration
D. Sheridan, General Motors

12:00 - 1:00 **Lunch**

1:00 - 3:30 **State of the Art**

Sources of Frictional Variations that Induce Vibrations
K. Ludema, University of Michigan
Contact Dynamics and Instantaneous Friction
A. Soom, State University of New York, Buffalo
Laboratory Measurements of Friction

P. Blau, Oak Ridge National Laboratory
Friction Instabilities in Elastomers and Plastics
N. Eiss, Virginia Tech
Control of Machines with Friction
B. Armstrong-Helouvry, University of Wisconsin, Milwaukee

3:30 - 4:00	**Break**
4:00 - 6:00	**Breakout Sessions (Concurrent)**
6:00 - 7:00	**Cocktails**
7:00	**Dinner**

NSF/ASME Workshop on Research Needs
in Friction/Vibration Interaction

Tuesday, August 9, 1994
Holiday Inn - University Center
100 Lytton Avenue
Pittsburgh, Pennsylvania

8:00 - 8:30	**Continental Breakfast**
8:30 - 10.00	**Breakout Sessions (Concurrent) - continued**
10:00 - 12:00	**Reports of Breakout Sessions - General meeting**
12:00 - 1:00	**Lunch**
1:00 - 3:00	**Summary of Recommendations & Discussion**
3:00 - 5:00	**Report Compilation by Steering Committee**

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