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CENTER FOR AEROSPACE STRUCTURES

NANOMECHANICS OF ACTIVELY CONTROLLED DEPLOYABLE OPTICS

Report for the Period 1998-1999

by

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This is the report for the research project entitled "Nanomechanics of Actively Controlled Deployed Optics" for the period 3/11/1998-12/31/1999.

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1.0 Introduction and Document Scope

This document is the interim, annual report for the research grant entitled "Nanomechanics of Actively Controlled Deployed Optics." It is supported by NASA Langley Research Center Cooperative Agreement NCC-1-281. Dr. Mark S. Lake is the technical monitor of the research program.

This document reports activities for the year 1998, beginning 3/11/1998, and for the year 1999.

The objective of this report is to summarize the results and the status of this research. This summary appears in Section 2.0.

Complete details of the results of this research have been reported in several papers, publications and theses. Section 3.0 lists these publications and, when available, presents their abstracts. Each publication is available in electronic form from a web site identified in Section 3.0.

2.0 Summary of Research Results

This research is a collaborative effort with NASA LaRC to develop basic technology for the deployment of optical spacecraft instruments. As part of this research team, CU provides basic research in support of the overall development effort by performing experiments and developing analytical models in the following areas:

- Nanometer resolution models of component latches, joints, actuators and optical mechanisms
- Basic constitutive modeling of interfaces, structural materials, and smart materials at nanostrain levels
- Passive and active stability of deployed reflector and truss prototypes at nanostrain levels

Through these three activities, the objectives of this research program are:

- Extend our ability to model lightweight structures, mechanisms and actuators to parts-per-billion levels as needed for the design, analysis, integration and test of flight systems.
- Identify through experimentation and analysis microdynamic phenomena, which are relevant to active control of deployed structures.
- Demonstrate the trade of passive vs. active control.
- Identify any new mechanical phenomena relevant to the engineering of actively controlled precision deployable structures and develop engineering approaches to their mitigation and control.
- Extend our ability to deploy lightweight ($<7 kg/m^2$) optical reflectors at low cost.

The progress to date and the ongoing activities in this research are summarized in the following subsections. Each subsection summarizes one of the three main foci of this research.

2.1 Component Models of Mechanisms

In this part of the research program, the objective was to develop models of mechanism hysteresis from known principles of contact mechanics. This part of the research has been completed, and was reported in the doctoral thesis by Hachkowski in Reference [1]. The abstract is presented in Section 3.0 below.

The principal results and contributions of this dissertation were:

- Development of an analytical model for the hysteresis behavior of deployment mechnisms.
- Development of the "Load Path Management" design approach for minimizing hysteresis in deployment mechanisms.
- Development of non-dimensional parameters which govern the hysteresis behavior of deployment mechanisms.
- Development of design recommendations which were later incorporated into the deployment mechanisms of the NASA LaRC LIDAR test article

2.2 Constitutive Behavior of Friction at Nanometer Deformation

This portion of the research program intended to consider whether structural instability due to friction is intrinsic to friction. The question was whether contact mechanics, as considered in Reference [1], is sufficient to predict the stability of precision mechanisms, or are other effects important. Such effects included potentially unknown friction mechanics at nanometer levels of deformation.

This part of the research has also been completed, and was reported in the doctoral thesis by Hinkle in Reference [2]. The abstract is also presented in Section 3.0 below.

The principal results and contributions of this dissertation were:

- Experimental characterization of the intrinsic nature of roughness-induced microslip at nanometer levels of deformation.
- Experimental identification of new, transient instabilities due to friction at nanometer levels of deformation.
- Development and validation of theoretical models of frictional microslip.

2.3 System Level Experimentation and Modeling

This portion of the research program is largely on-going at the time this report is being prepared. The subsections below describe both progress to date and current activities.

2.3.1 Dynamic Stability Experiments on the ESDM Test Article

A major accomplishment of this phase of the project was the experimental measurement of the nanometer level stability of the NASA LaRC ESDM test article. The ESDM (for "Experimental Science Development Model") was the subject of prior tests reported in the Doctoral Dissertation by Warren[1] which first identified the "microlurch" and "equilibrium zone" mechanical phenomena.

The purpose of the experiments performed under this grant was to interrogate the dynamic stability of the structure to very low frequency mechanical loads. The intent was to measure the presence or absence of anomalous, high frequency responses developed in the structure from these low frequency loads.

The prior tests had insufficient resolution of the dynamics of the test article below approximately 0.25 microns of displacement. The experiments performed under this grant extended this resolution through the use of new experimental techniques developed by Hardaway in the thesis proposed in Reference [3]. This thesis is expected to be completed shortly after the publication of this report, and it will contain complete details of the results.

The primary result of these experiments is that low frequency loads applied to the ESDM test article produce high frequency vibrations at sub-micron levels of motion. The data will be presented and analyzed in the up-coming doctoral dissertation by Hardaway .

Companion experiments done subsequently for JPL on the IPEX Single Bay test article, also showed anomalous vibrations at sub-micron and nanometer levels of deformation. These too are being reported in an upcoming thesis by Hardaway.

Future tests, in particular those on the NASA LaRC LIDAR test article, will need to directly instrument the joints and mechanisms to determine whether slippage has in fact occurred when such a

[1] Warren, P.A. and Peterson, L.D. "Sub-Micron Non-Linear Shape Mechanics of Precision Deployable Structures" Doctoral Dissertation. Report No. CU-CAS-96-18. July 1996.

vibration is observed. They will also need higher resolution load measurement and application devices than were used in these experiments.

2.3.2 Implications for Active Control of Deployed Reflectors

New doctoral thesis research, under the sponsorship of this grant, is investigating the implications of nanometer level structural instability on active control. The objectives are to consider the following issues:

- What are the implications of static instabilities such as permanent hysteresis on active control architectures and algorithms?
- What are the implications of dynamic instabilities on active control architectures and algorithms?
- Some observed instabilities seem to occur spontaneously, and unpredictably. Can these be controlled without increasing the bandwidth of the control system to include a multitude of structural modes?
- How do active adjustment elements affect the overall stability of the deployed optic? Does the addition of active control affect the overall passive stability of the system?
- What drives the trade between active and passive control in deployed reflector systems?

At the time of publication of this report, these questions are being narrowed and further developed by two doctoral research assistants who are both preparing thesis proposals to be presented sometime in 2000.

2.3.3 Preparation for Nanometer Stability Experiments on the LIDAR Test Article

As part of the continuing efforts to further refine our understanding of the stability of deployed optical systems, this research is preparing for experiments on the NASA LaRC LIDAR deployed reflector test article. This structure uses design and analysis principles developed from research sponsored by this grant to reduce the permanent hysteresis in the deployment mechanisms.

The upcoming experiments on the LIDAR test article will have the following objectives:

- Confirmation of the deployment precision and microlurch mechanics with nanometer levels of resolution.
- Comparison with a theoretical model of the deployment precision and post-deployment mechanical stability
- Examination of the dynamic stability of the test article under nanometer levels of deformation
- Answer whether static mechanical hysteresis predicts in some way the dynamic stability of the deployed structure.

The principle contribution to experimental science in this experiment has been the development of a new, high resolution metrology system for measuring the deployment precision with nanometer level resolution.

2.3.4 DARKSTAR Senior Project: A Student-Built Precision Deployable

As with many of our research activities, this grant also influenced the development of undergraduate capstone engineering design projects. One of these was the DARKSTAR project, developed in 1998.

The acronym DARKSTAR stood for "Dynamic Actuator Released Kinematic Space Telescope Application of a Repeatable Deployment System." A copy of the final presentation can be found in Reference [11]. The project developed an alternative version of the ESDM and the LIDAR test article deployment concepts. DARKSTAR used a four-bar linkage mechanism to accomplish the deployment of the structure. The revolute joints of the test article incorporated the design developed by NASA LaRC for the ESDM and the LIDAR. The students designed and constructed the test article over the period of two semesters.

Measurements of the deployment repeatability of this test article demonstrated deployment errors on the order of 4 microns. This was the error following deployment without inducing "microlurches" into the "equilibrium zone" of the test article. A comparable error in the ESDM experiments performed under a prior grant with NASA LaRC would be 10-20 microns of deployment error.

As the observed error was also on the order of the accuracy of the test apparatus, the actual repeatability of the test article might have been better than these results appear to indicate. Unfortunately, subsequent tests have not been performed to further refine or examine this data.

3.0 Publications, Papers and Presentations Sponsored by this Research

The publications to date that were sponsored by this research or were co-sponsored by this research are listed below.[2] Where applicable, complete abstracts of the work are included.

It should be noted that many of the publications listed below were sponsored by more than the research grant for which this is the annual report. In many cases, multiple authors were sponsored by different activities and agencies, or the research spanned multiple contracts or grants. Complete listings of the research sponsorship is acknowledged in each paper and report.

Acrobat PDF versions of the publications are available at the web site:

http://sdcl-www.colorado.edu/Publications/Default.html

3.1 Doctoral Theses

[1] **Hachkowski, M.R. "Reduction of Hysteresis in the Load-Displacement Response of Precision Deployment Mechanisms through Load Path Management" University of Colorado, May 1998.**
Report No. CU-CAS-98-07.

The ability to deploy lightweight structures to near optical precision is an important technical challenge remaining in the development of deployable space structures. The performance of telescopes, interferometers, and high frequency data communication systems that require precision deployable space structures is limited by deployment accuracy and kinematic stability. While several sources of error contribute to structural uncertainty, it is hysteresis in deployment mechanisms which is perhaps the most significant source of dimensional uncertainty in high-precision deployable structures. The traditional approach to achieving high precision in deployable structures is to minimize nonlinearities in the load-displacement response of the deployment mechanisms by highly preloading the mechanical interfaces within the mechanisms. While this approach is effective at reducing or eliminating freeplay and some other types of nonlinear response, it can lead to an increase in the amount of hysteretic response. Until now, there has been inadequate theoretical characterization of the hysteretic response in precision deployment mechanisms to enable specific design guidelines to be established for reducing this response.

This thesis provides the first theoretical understanding on how to reduce hysteresis in a precision mechanism by reducing load transfer across friction interfaces. It is demonstrated that load transfer across friction interfaces can be reduced by changing the relative magnitudes of internal stiffness. While an increase in assembly preload could reduce/remove nonlinear elastic response and freeplay, it is found and demonstrated that an assembly preload could increase the hysteretic response of a rolling element joint. Preload increases dissipation by both increasing the magnitude of the friction mechanism as well as changing the relative stiffness magnitude such that the portion of load transfer across a friction interface increases.

To this end, an analytical multi-body rolling element model representing a deployable joint with internal interface mechanics is presented for the purpose of (i) identifying friction and nonlinear stiffness interface mechanisms within a joint and (ii) understanding how friction mechanisms are coupled to the quasi-static response of elastic mechanisms. From the model, it is determined that the dimensions of the rolling elements are critical in tailoring the hysteretic-response of a rolling

[2] References [1], [4] and [6] listed below were sponsored under a prior NASA LaRC research grant NAG1-1840, but have not been previously identified in a contract report to NASA.

element joint. This model demonstrates that by affecting the strain energy distribution within the component, one can decrease the load transfer across internal hysteretic mechanisms.

[2] Hinkle, J.D. "Frictional Microslip Due to Roughness in Metallic Interfaces at the Nanometer Scale" University of Colorado, July 1998.
Report No. CU-CAS-98-12.

This thesis investigates the frictional shear behavior of metallic interfaces prior to gross sliding. The focus is the nanometer scale friction in the latches, joints, and other mechanisms found in optically precise deployable spacecraft structures.

The thesis examines in particular a hysteretic load-displacement behavior called microslip that occurs prior to gross sliding in interfaces. Prior investigations in the contact mechanics and friction literature suspected that interface roughness might substantially determine the microslip mechanics at submicron and nanometer scales. But because the prior work had insufficient scope and measurement resolution, new experiments were conducted in this thesis to resolve microslip mechanics with nanometer precision.

These experiments identified several previously unrecorded microslip characteristics which are likely to impact the microdynamic stability and vibration of precision deployable structures. In particular, a significant and sometimes sudden transient behavior following initial loading of the interfaces is exhibited in the compliance and hysteresis of the shear response. This eventually diminishes to steady-state levels after perhaps dozens of cycles, but recurs after reassembling the interface. Extensive data was also gathered on the steady state hysteresis, which is shown to decrease with additional normal stress across the interface. However, friction hysteresis was never observed to diminish to zero, even at nanostrain load levels.

A theoretical model is compared with the experiment. The model is not empirical, but is derived from the constitutive elasticity and roughness of the interface. Theoretical assumptions from prior work are brought into question by this comparison. For example, although the measured and simulated frictional hysteresis agree qualitatively, the absolute accuracy of the model is generally poor. Subsequent analyses of the surface structure and asperity mechanics assumptions indicate both are significantly in error. Additional disagreements with the measurements also question the assumptions of prior theory. In particular, the model does not generally reproduce the transient behavior observed in the mechanics. Also, the fact that the rougher surfaces had lower hysteresis disagrees with the theory as well. The conclusion is that the general form of the model may be credible, but the details of surface structure and asperity mechanics deserve more attention.

3.2 Thesis Proposals

[3] Hardaway, L.M.R. "The Nanodynamic Response of Precision Deployed Optical Structures" Doctoral Thesis Proposal, November 18, 1998.
Report No. CU-CAS-98-23.

A thesis proposal is introduced which determines how and why dynamic responses can be generated from quasi-static loads in precision deployable structures due to microdynamic nonlinear mechanisms. The common engineering presumption that preload prevents nonlinearity at a nanometer scale is fundamentally unsupported by the literature. This proposal investigates the microdynamic response of precision deployable structures through experimentation.

The design, development and characterization of a novel ground facility for testing optically precise deployable structures is described. The effects of individual systematic errors, which if neglected could lead to falsely exotic mechanics, are discussed.

The microdynamic stability of two composite articles is experimentally assessed. Measurements were obtained using a new test facility with nanometer resolution. These tests confirm the absence of acoustic emissions in composite components for sufficiently low stress levels.

The microdynamic stability of a deployed optical truss under the application of quasi-static mechanical and thermal loads is experimentally assessed. A threshold of load rate and amplitude is determined which defines the nanometer level stability margin of the structure.

A brief review of the work to date is presented, along with the limitations of this work. A plan for overcoming these limitations through the use of multiple test articles and more precise experimentation is presented. The test configuration and protocols for pending tests are described.

3.3 Papers

[4] **Lake, M.S., Peterson, L.D., Hachkowski, M.R., Hinkle, J.D., and Hardaway, L.R. "Research on the Problem of High-Precision Deployment for Large-Aperture Space-Based Science Instruments" 1998 Space Technology and Applications International Forum, January, 1998.**

The present paper summarizes results from an ongoing research program conducted jointly by the University of Colorado and NASA Langley Research Center since 1994. This program has resulted in general guidelines for the design of high-precision deployment mechanisms, and tests of prototype deployable structures incorporating these mechanisms have shown microdynamically stable behavior (i.e., dimensional stability to parts per million). These advancements have resulted from the identification of numerous heretofore unknown microdynamic and micromechanical response phenomena, and the development of new test techniques and instrumentation systems to interrogate these phenomena. In addition, recent tests have begun to interrogate nanomechanical response of materials and joints and have been used to develop an understanding of nonlinear nanodynamic behavior in microdynamically stable structures. The ultimate goal of these efforts is to enable nanoprecision active control of microprecision deployable structures (i.e., active control to a resolution of parts per billion).

[5] **Lake, M.S., Peterson, L.D., Mikulas, M. M., Hinkle, J.D., Hardaway, L.R., and Heald, J., "Structural Concepts and Mechanics Issues for Ultra-Large Optical Systems" *Proceedings of the Ultra-Lightweight Space Optics Workshop*, Napa, CA, March, 1999.**

(No abstract available.)

[6] **Hachkowski, M.R., Peterson, L.D. and Lake, M.S., "Analytical Model of Nonlinear Hysteresis Mechanisms in a Rolling Element Joint" AIAA-99-1268, *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, St. Louis, Missouri, 12-14 April, 1999.**
Paper No. AIAA-99-1268.

Both elastic and friction nonlinearities exist in complex mechanisms and joints. Whereas elastic nonlinearities in joints and mechanisms such as variable stiffness, bilin-earity and freeplay can lead to nonlinear structural dy-namics, inelastic joint nonlinearities such as hysteresis can limit the static shape performance of large deployable space structures. Hysteresis in structures can be caused by friction that exists at structural interfaces or inelastic mechanisms within the structure's material. A multi-body rolling element joint model that represents a deployable joint and includes the interface mechanics of multiple elastic bodies is presented for the purpose of (i) identifying hysteretic mechanisms due to interface mechanics within a joint and (ii) understanding how the hysteretic mechanisms change in the presence of monotonically varying internal forces. With the multi-body model, it will be shown how the hysteretic mechanisms within the joint are dependent of internal forces and geometries and how the cumulative effect of the various hysteretic mechanisms within the joint affects the overall joint hysteretic-response behavior. The significant contribution of the paper is the inclusion of the friction microslip in the analytical joint model and the effect the friction microslip has on the overall hysteretic-response behavior of the deployable joint. As well, the paper presents an approximate method in calculating the friction torque of a rolling ball bearing in the presence of monotonically varying normal loads.

[7] **Hardaway, L.M.R. and Peterson, L.D., "Ground-Based Microdynamic Testing of Deployed Optical Structures" AIAA-99-1273, *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, St. Louis, Missouri, 12-14 April, 1999. Paper No. AIAA-99-1273.**

The design, development and characterization of a new and unique ground facility for testing optically precise deployable structures is described. Through careful control and elimination of subtle systematic error sources, this facility allows the characterization of the mechanics of deployed structures up to 3-meters in size with nanometer resolution. This paper itemizes the effect of individual systematic errors and shows how experimental measurements which otherwise neglect these effects lead to falsely exotic mechanics. Implications of this research for the ground testing of deployed optical spacecraft instruments are also described.

[8] **Hinkle, J.D. and Peterson, L.D., "An Experimental Investigation of Roughness-Induced Microslip in Metallic Interfaces" AIAA-99-1382, *Proceedings of the 40th Structures, Structural Dynamics, and Materials Conference*, St. Louis, Missouri, 12-14 April, 1999. Paper No. AIAA-99-1382.**

This paper presents the results of an experiment performed to examine the presliding behavior of dry metallic interfaces. In particular, a hysteretic load-displacement behavior termed microslip is studied. These experiments identified several previously unrecorded microslip characteristics which are likely to impact the microdynamic stability and vibration of precision deployable structures. In particular, a significant and sometimes sudden transient behavior following initial loading of the interfaces is exhibited in the load-displacement response. This eventually diminishes to steady-state levels after perhaps dozens of cycles, but recurs after reassembling the interface. Extensive data was also gathered on the steady-state hysteretic behavior which is shown to decrease with additional normal stress across the interface. However, friction hysteresis was never observed to diminish to zero, even at nanometer levels of motion.

3.4 Presentations

[9] **Peterson, L.D., Hardaway, L.R., Hachkowski, M.R. and Hinkle, J.D. "Microdynamics and the Road to Predictive Structural Models" Presented at the 16th International Modal Analysis Conference, February, 1998.**

[10] **Peterson, L.D., Lake, M.S., Hardaway, L.R., Hachkowski, M.R., Hinkle, J.D., Domber, J., and Klumpon, C "A Review of Current Microdynamic Research Activities" Presented at the 4th Semi-Annual Microdynamics Workshop, Boulder, Colorado, April 29, 1998.**

[11] **Conly, L., Espinosa, M., Iranpour, K., and Jakubek, M. "Dynamic Actuator Released Kinematic Space Telescope Application of a Repeatable Deployment System (DARKSTAR)" Senior Projects Final Report, May 7, 1998.**