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Evro Wee Sit *Editor*

Sensors and Instrumentation, Volume 5

Proceedings of the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015

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Preface

Sensors and Instrumentation represents one of ten volumes of technical papers presented at the 33rd IMAC, A Conference and Exposition on Structural Dynamics, 2015, organized by the Society for Experimental Mechanics, and held in Orlando, Florida February 2–5, 2015. The full proceedings also include volumes on Nonlinear Dynamics; Dynamics of Civil Structures; Model Validation and Uncertainty Quantification; Dynamics of Coupled Structures; Special Topics in Structural Dynamics; Structural Health Monitoring and Damage Detection; Experimental Techniques, Rotating Machinery and Acoustics; and Shock and Vibration Aircraft/Aerospace, Energy Harvesting; and Topics in Modal Analysis.

Each collection presents early findings from experimental and computational investigations on an important area within Sensors and Instrumentation. Topics represent papers on calibration, smart sensors, rotational effects, stress sensing and tracking of dynamics. Topics in this volume include:

Experimental Techniques
Smart Sensing
Rotational Effects
Dynamic Calibration

The organizers would like to thank the authors, presenters, session organizers, and session chairs for their participation in this track.

Hermosa Beach, CA, USA

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Contents

Chapter 1
LLCD Experimental Line-of-Sight Jitter Testing

Brandon J. Dilworth

Abstract The LLCD program at MIT Lincoln Laboratory is the first space laser communication system for NASA. The optical communications terminal was carried into lunar orbit by the LADEE spacecraft which launched on September 6, 2013. The primary goal of the LLCD program is to demonstrate optical communication from lunar orbit to the Earth's surface.

Optical communication systems have many advantages over RF systems which include achieving higher data rates using lower size, weight and power (SWaP). Optical communication systems rely on much narrower beams than RF systems to achieve these advantages; the penalty is that the optical beam must have good stability in order to maintain the communication link between the transmitter and receiver. There are a number of factors that play a role in the stability of the optical beam, but the focus of this talk is on the residual LOS jitter resulting from unrejected spacecraft excitation. Experimentation with physical hardware is a common method for validating mathematical models, including residual LOS jitter models. The LLCD program developed a test bench in order to validate the residual LOS jitter model which provides higher confidence in the computational results.

Keywords LOS jitter • Optical communication • Model validation • MIMO sine testing • LLCD

Nomenclature

DOF	Degree of Freedom
FEM	Finite Element Model
ICD	Interface Control Document
IR	Infrared
LADEE	Lunar Atmosphere and Dust Environment Explorer
LLCD	Lunar Laser Communication Demonstration
LOS	Line-of-Sight
MAC	Modal Assurance Criterion
MIMO	Multiple Input Multiple Output
MIRU	Magneto-hydrodynamic Inertial Reference Unit
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
PSD	Power Spectral Density
RF	Radio Frequency
SNR	Signal-to-Noise Ratio

Statement
This work is sponsored by the National Aeronautics and Space Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

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1.1 Introduction

The LLCD program developed and fielded the first duplex laser communication system for NASA. MIT Lincoln Laboratory designed and built a space terminal for lunar orbit and the primary ground terminal to execute the demonstration. A month after launch, the LLCD system demonstrated a 20 Mbps uplink and a 622 Mbps downlink between the Moon and the Earth. Both links represent data rates much higher than ever achieved previously over that distance. An overview of the system architecture and demonstration results have been previously published [1].

Optical communication systems use much shorter (>10,000×) wavelengths as compared to existing RF communication systems. The shorter wavelengths enable large bandwidth modulation, higher data rates and low diffraction losses as compared to RF systems. The shorter wavelength results in a narrow beamwidth which means that the optical terminals (at both ends of the link) can be much smaller and require less power than their RF counterparts. However, a narrow beamwidth means beam stability becomes a much more significant challenge. For the LLCD space terminal, the resulting requirement was that the beam had to be stabilized better than 4.2 μrad to maintain the communication link.

The space terminal optical module included several features in order to achieve the pointing requirements which are graphically summarized in Fig. 1.1. Initial pointing of the terminal is executed by the spacecraft with accuracy based on the performance of its star trackers. The 2-axis gimbal provides coarse pointing while the MIRU provides the fine pointing and inertial stabilization of the optical head. The telescope is an all-beryllium structure with a 10 cm primary mirror. The approach of the control system and the architecture of the optical paths have been described previously [2].

1.2 Line-of-Sight Jitter

Line-of-sight jitter is simply defined as the time-varying motion of the image on the detector plane [3]. In imaging systems (like cameras), LOS jitter can result in blurred images. In laser communication systems, LOS jitter can result in loss of data rate. In both scenarios, the LOS jitter can be induced either internally from or externally to the system. Typical sources of self-excitation are due to the tracking system mechanism(s). On the LLCD Space Terminal, the dominant sources of self-excitation were due to the Gimbal motion (stepper motors) and the nutation mechanism on the Optical Head. Primary sources of external excitation were due to the reaction wheels on the LADEE spacecraft coupling through the spacecraft structure and acting as base excitation to the Instrument Panel. The external excitation was prescribed early in the program based on

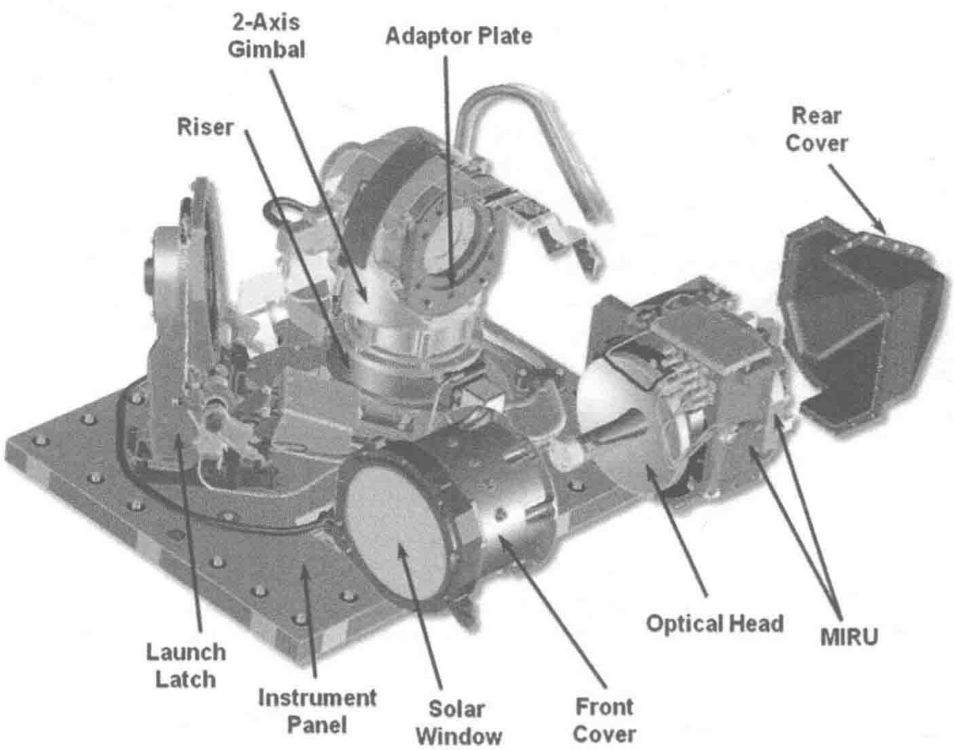

Fig. 1.1 LLCD space terminal optical module

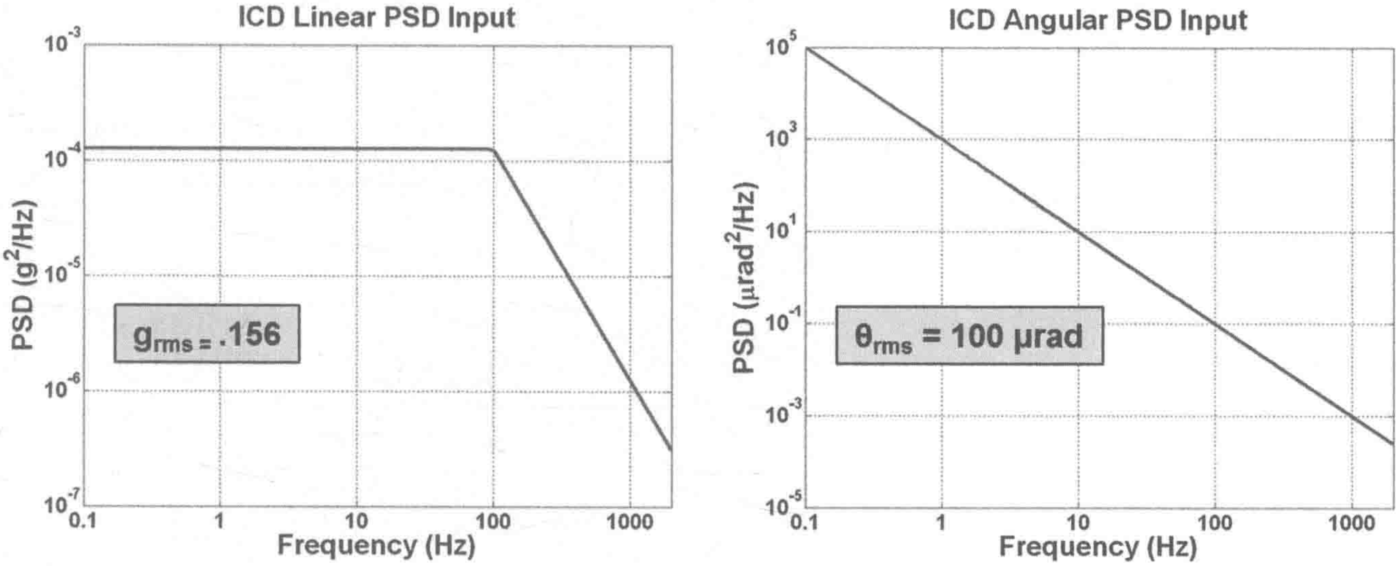

Fig. 1.2 Excitation disturbance defined at instrument panel

previous experience of the team, and was defined in the ICD as shown in Fig. 1.2. From the angular disturbance alone, it is apparent that some stabilization control is required to bring the 100 μrad disturbance down to less than 4.2 μrad of residual LOS jitter.

As system performance is greatly dependent on the LOS jitter performance, a computational model was developed to study design tradeoffs and to verify system requirements [4]. The modeling efforts went through several iterations of validation and updating throughout the program [5]. The focus of this paper is on the experimental efforts which supported the model validation of the LOS jitter computational model.

1.3 Test Setup

Conceptually, the LOS jitter test bench needed to provide three functions: base excitation to the Optical Module, dynamic measurement of the excitation at the base of the structure and dynamic measurement of the beam position. Practically, several tradeoffs were considered when developing the test bench which balanced cost with resultant data. One significant assumption used when weighing the tradeoffs was that the structure would act as a linear system during test. The advantage of the structure assumed to be a linear system meant that the input excitation would not need to match the ICD disturbances exactly, which greatly simplifies the design requirements on the test setup and test fixture structure.

In order to provide base excitation to the system the test fixtures needed to be able to support the weight of the Optical Module and all of the test fixtures, provide 6-DOF motion at the base of the Optical Module, and needed to have provisions for incorporating exciters. A product sold as an isolator system was cable of supporting both the weight of the test structure and provide the 6-DOF motion. Electro-dynamic exciters were selected to provide the base excitation to the test structure, connected through additional fixtures. The shakers were sized based on the prescribed ICD linear acceleration and the expected mass of the test structure (Optical Module plus all additional fixtures). A second isolation table provided the reaction mass for the shakers in addition to providing isolation from any environmental/room excitation. In an effort to keep test fixture costs down, only three shakers were included in the setup which did not enable all 6-DOF's to have similar excitation levels concurrently. However, arranging the shakers into multiple configurations enabled all 6-DOF base motion to be evaluated.

Dynamic measurement of the excitation at the base of the Optical Module was enabled by a triaxial accelerometer and three angle rate sensors to characterize the 6-DOF motion. The angle rate sensors enabled measurement of the angular DOF's directly, which helped reduce opportunities for measurement errors as compared with post-processing several accelerometer sensors configured in a geometry such that angular DOF's could be calculated. The accelerometer was mounted near the pivot point of the angular DOF's to passively minimize effects due to the angular excitation. The angle rate sensors were mounted at the perimeter of the instrument panel of the Optical Module. Figure 1.3 shows the test structure with the Optical Module under test in one (of multiple) shaker configurations.

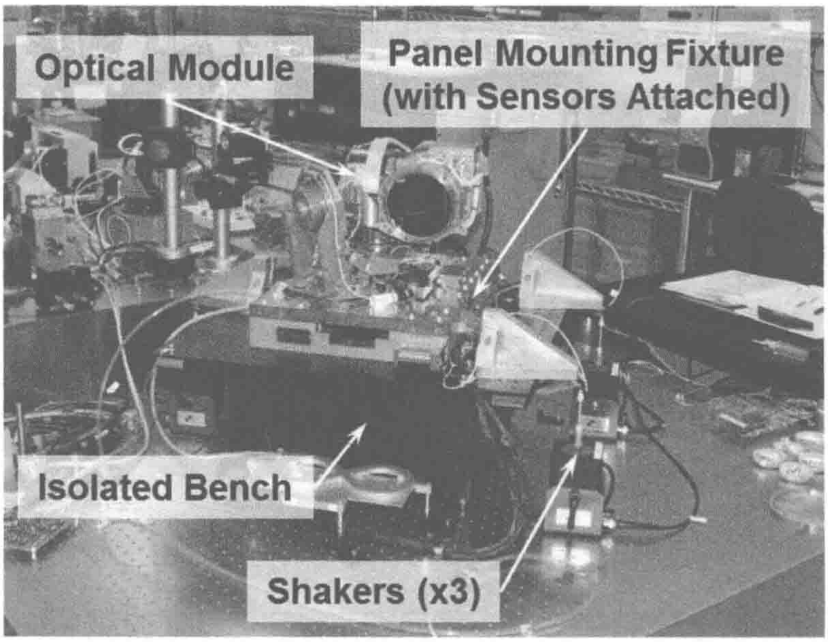

Fig. 1.3 Photograph of test setup

The dynamic measurement of the beam position was enabled through the use of an optical test bench. The details of the layout of the optical test bench are not described in detail in this paper, but the enabling sensor to measure the dynamic position of the beam was an IR camera. The IR camera output was coupled with a centroid estimating algorithm which operated at near a 4 kHz update rate. At the smallest frame size of the camera, the resolution of the centroid estimate was about 0.8 μrad which provided enough SNR to reliably capture the beam dynamics in the frequencies of interest. A graphical representation of the test setup is provided in Fig. 1.4 which provides an overview of the entire test setup architecture.

1.4 Test Methodology

As stated before, this experimental effort was in support of model validation of the FEM developed to predict overall residual LOS jitter performance. With that perspective in mind, the test bench was developed to target the frequencies which were predicted to be the most predominant in the context of LOS jitter. It was this perspective which drove the test bench to be capable of supporting a test bandwidth of 5–1,000 Hz.

Initial estimates from the FEM suggested that the first flexible modes related to bending of the gimbal had the most dominant role, which were initially predicted to be near 60.3 Hz. The MIRU had an internal mode near 11 Hz and even though it was assumed that this mode would be mitigated by the inertial stabilization loop, this frequency was used as one bound to define the lower excitation frequency of the test bench. The angle rate sensors used to measure the angular DOF's of the test bench described previously have a useable bandwidth of 5–1,000 Hz. Although other constraints were considered to limit the low frequency excitation of the system (such as stroke limits of the exciters and the isolation table), 5 Hz was selected primarily based on the usable bandwidth of the angle rate sensors.

A typical approach to presenting LOS jitter results is to show forward and backward cumulative RMS plots to compliment a PSD response. The FEM predicted LOS jitter response plots are shown in Fig. 1.5 which provided initial insight to system performance. The FEM predicted that excitation frequencies above 500 Hz would have minimal impact to the overall residual LOS jitter (cumulative sum above 500 Hz roughly 10× below total). In order to validate that prediction with confidence, the upper bound test frequency was selected to be 1,000 Hz.

Due to resource availability, the excitation method was developed using a preliminary optical test bench. Initial characterization of the preliminary test bench indicated that the noise floor of the optical response was much higher than expected. As a result, MIMO sine control excitation using force feedback at the stinger attachment points was selected to drive the base motion of the system. Both stepped and swept sine excitation methods were evaluated and swept sine was determined to provide the best trade-off between fidelity of the data and time of test execution. Random excitation was evaluated, but excitation levels could not be driven at high enough levels to provide reliable measurements above the sensor noise floor of the initial optical test bench. Although the final optical test bench had greatly improved performance, as noted above, the entire base excitation test procedure was developed using the initial optical test bench.

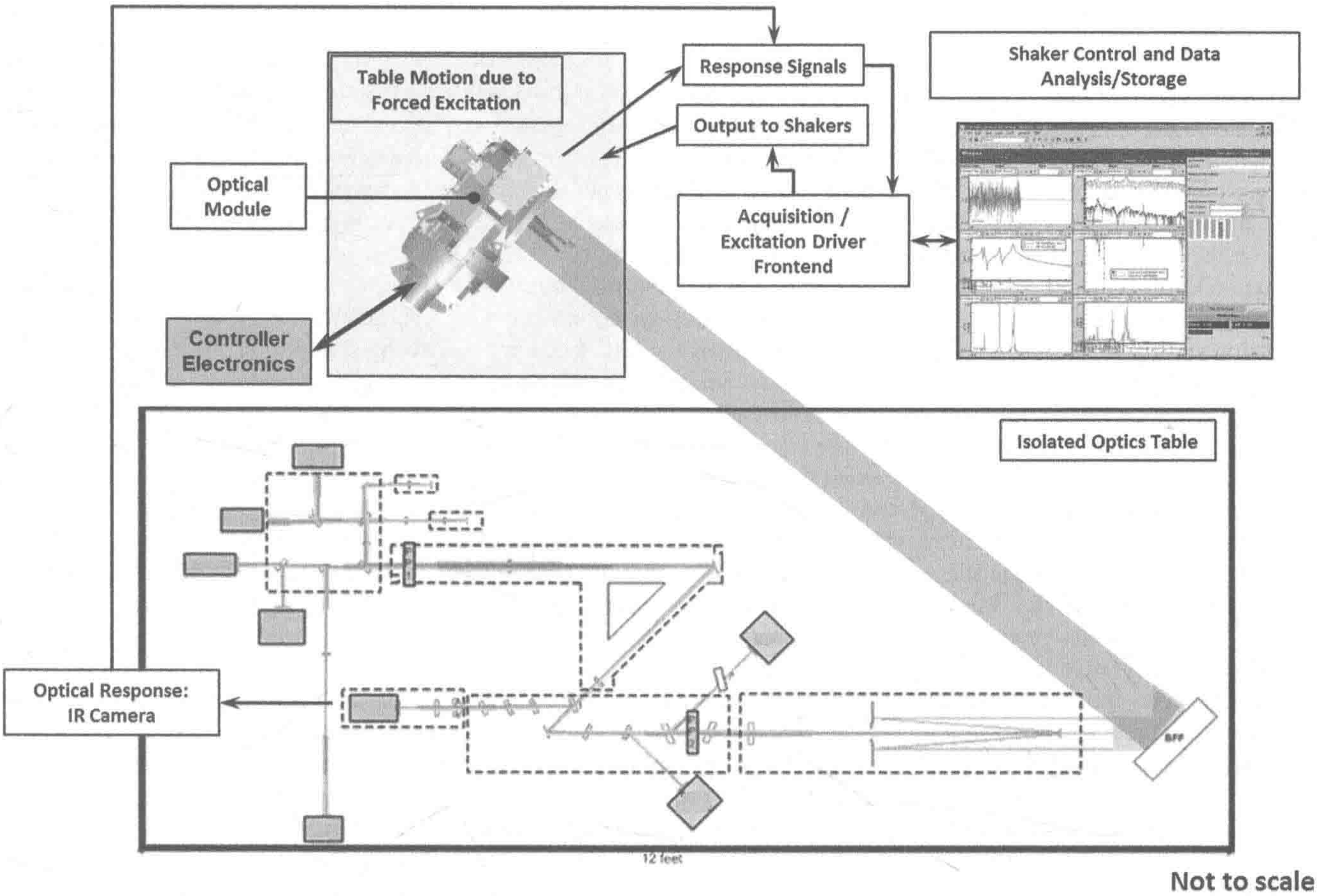

Fig. 1.4 Test setup architecture

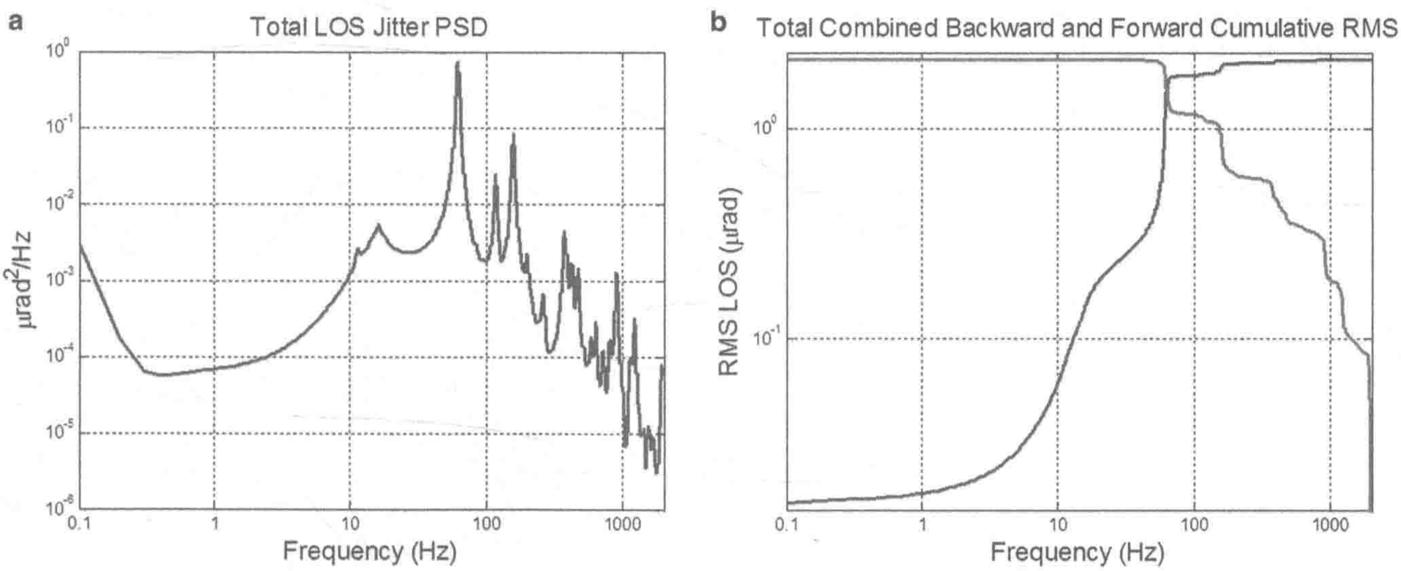

Fig. 1.5 FEA predicted LOS jitter response PSD (a) and corresponding cumulative RMS (b)

1.5 Test Execution

One of the very first tests conducted was to verify that the excitation provided to the base of the optical module would not propagate to the optical test bench. A simple transmissibility test was conducted using a fixed light source on the optical test bench in addition to placing seismic accelerometers on the bench. The triaxial accelerometer on the base of the optical module was used as the reference signal. Although the quantitative data is not shown in this paper, there was no resolvable evidence (with the sensors used) of the shaker excitation propagating to the optical test bench. As an isolated optical bench was used both on the optical test bench and on the optical module base excitation test bench coupled with low (but representative) excitation levels provided to the system, the measure of low transmissibility was not surprising.

Another set of tests were executed to validate the linear system assumption. Although it was expected that the 2-axis gimbal would act non-linear in many different conditions, the test structure was linearized to within 1 % (based on modal frequencies) by bounding the input excitation levels based on the ICD base excitation disturbance. Base excitation was provided to the optical module and data were processed as an operational modal test using the accelerometer at the base of the optical module as the phase reference. The test was conducted in this manner as the shaker attachment points were not on the test structure itself, but rather attached to test fixtures which precluded the opportunity of running a more classical modal test. Data shown in Fig. 1.6a identifies a sub-set of crosspowers used to curve fit the modal parameters and the modal frequency results indicating linearity within 1 % between all of the excitation levels. Figure 1.6b shows the MAC analysis between two sets of the mode shape vectors which indicate that the mode shapes are consistent at the different excitation levels as well. These results validated the linear system assumption for the excitation levels prescribed for the LOS jitter testing. These tests also provided the data to support the model updating described in previously [5] which improved the model results from over 25 % error down to within 3.5 % error.

Once the final optical test bench was operational, a set of tests were conducted to characterize its dynamic response with a fixed light source. As shown in Fig. 1.4, there are several optical elements in the optical path. Each optical element has its own mounting structure and is typically mounted to the optical bench using bolted attachments. There are several elements in the optical path that have mounting structures with tip/tilt adjustment. For the adjustable mounts used on this optical bench, the adjustment mechanism was spring-loaded. A point not mentioned previously is that all optical tests were conducted in a clean room environment. A consequence of operating in a clean room is that the air handling can have substantial effects on optical measurements. Other dynamic effects, such as floor excitation from the surrounding laboratory environment, were also presumed to influence the behavior of the optical measurement. In order to characterize and baseline the optical response due to the environmental conditions, a fixed light source was mounted on the optical test bench and data were collected at the IR camera. A photograph of the fixed light source is shown in Fig. 1.7a and the measured response is shown in Fig. 1.7b. There are two artifacts noted in the measured response. The first artifact is associated with the dynamics of the optical test bench due to the environmental conditions in the room. Fortunately, all of the dynamics associated with the

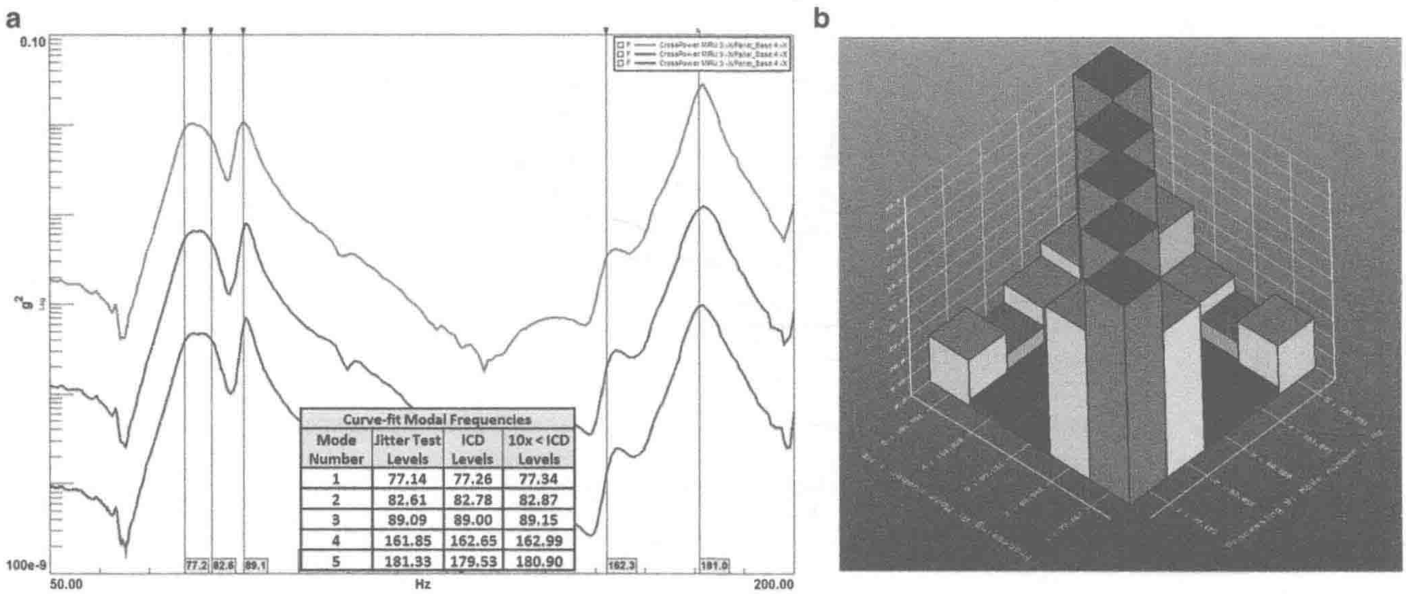

Fig. 1.6 Sub-set of crosspowers used to curve fit modal parameters (**a**) MAC calculation between two sets of mode shape vectors due to different excitation levels (**b**)

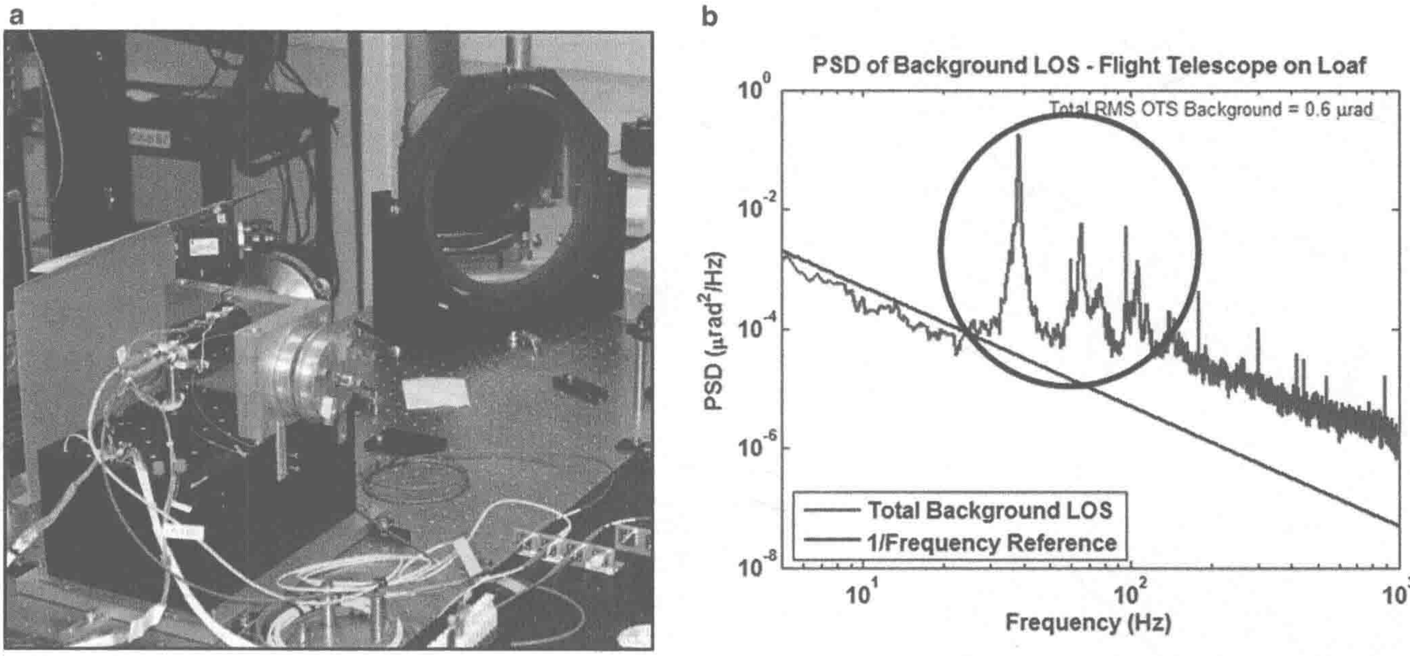

Fig. 1.7 Photograph of fixed light source (**a**) Response due to background environment (**b**)

optical response occur at different frequencies than the modes of the optical module. The second artifact is the typical 1/f or "flicker noise" which is associated with the digital IR camera electronics. This background measurement proved to be very useful to understand the full measurement chain in the LOS jitter measurement.

The last consideration prior to final LOS jitter testing was attempting to quantify the effects of the air handling between the optical module and the optical test bench. Although not shown to scale in Fig. 1.4, there was roughly 12 ft of open air space between the optical model and the first optical element on the optical test bench. Tests were conducted with varying amounts of passive approaches to mitigate the effects due to the airflow in the room. Simple structures such as tubes and tarps shown in Fig. 1.8a were used to quantify the effects. Results of the mitigation techniques are shown in Fig. 1.8b indicating up to a 3× improvement in the noise floor of the measurement, with the primary improvement noted in frequencies below 20 Hz.

Final LOS jitter testing applied all of the lessons learned based on previous experiments: defining input loads to the test structure, validating the linear system assumption for the LOS jitter input loads, characterizing the dynamics of the optical test bench, and mitigating effects due to the airflow in the clean room. Measurements were collected using multiple shaker configurations to allow each of the 6 base excitation DOF's to be excited at or above ICD levels. Combining these measurements verified that no one particular DOF dominated the LOS jitter response. The raw measured data from the LOS jitter experiment was post-processed to account for the background noise of the optical test bench and the fact that the experimental inputs exceeded the ICD excitation at most frequencies. Although the details of the post-processing are not described in this paper, the results provided evidence that the optical module would be able to meet its LOS jitter performance requirements. Coupling the post-processed results with the final updated FEM provided the last step in the successful model validation effort as shown in Fig. 1.9. Although the results do not overlay perfectly, the overall system behavior is well matched in the two data sets.

1.6 Conclusions

An experimental LOS jitter test bench was developed for the LLCD program which was used to validate the FEM used to predict performance. The LOS jitter test bench offered insight to the dynamics of the optical module which would have otherwise gone uncharacterized. Clear evidence was made to underline the advantage of such a test bench and highlight the versatility of such a test setup.

Conducting tests as operational modal tests enabled model updating where a classical modal test was not possible. Dynamic characterization of the optical test bench was essential to understanding the optical response and differentiating

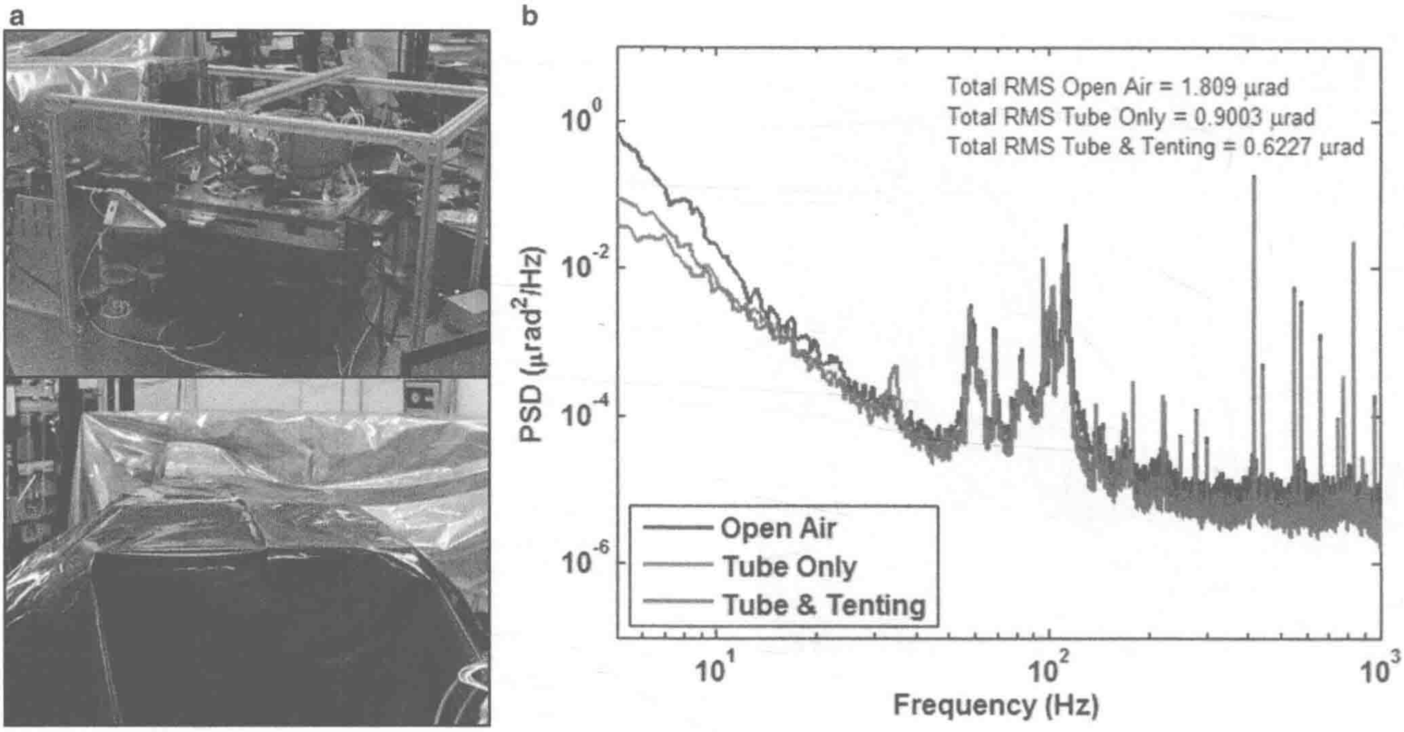

Fig. 1.8 Airflow mitigation (**a**) Results of passive airflow mitigation (**b**)

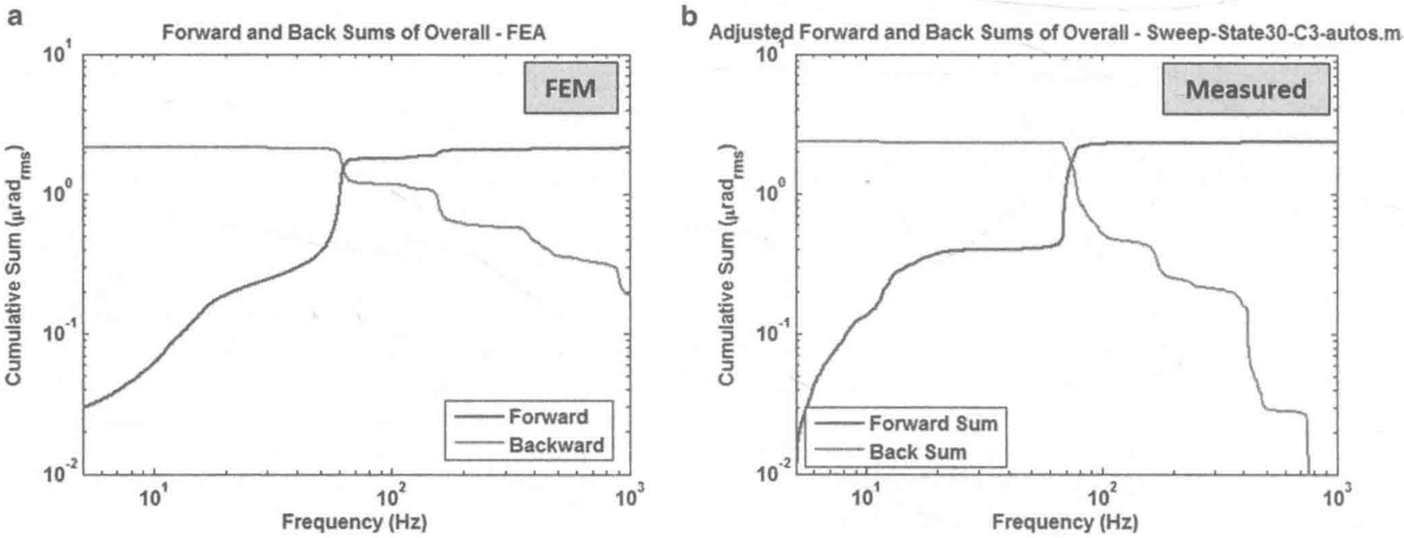

Fig. 1.9 FEM predicted LOS jitter (**a**) Post-processed measured LOS jitter results (**b**)

between optical module dynamics from optical response behavior. Passive airflow mitigation techniques proved to be helpful in improving the SNR of the measurement at lower frequencies.

The LOS jitter test bench enabled the FEM to be validated which provided confidence in final system performance prior to launch. Although the LOS jitter test bench offered the initial indication that the optical module would meet its performance requirements, the final validation occurred during the successful performance of the optical communication link while on orbit around the moon.

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Chapter 2
A Virtual Reality Glovebox with Dynamic Safety Modeling for Improved Criticality Regulation Visualization

Kyle Embry, Andrea Hengartner-Cuellar, Hannah Ross, and David Mascareñas

Abstract Technicians working in gloveboxes must vigilantly keep track of the locations of the radioactive materials they work with in order to make sure they do not inadvertently perform an action that can lead to a technical criticality safety violation. The administrative consequences of these mistakes can result in halting work in a facility and can be costly. The process currently used to ensure safe operations requires every two technicians to be monitored and documented by a third technician, thus resulting in large overhead costs. This work aims to help reduce the possibility of incurring an administrative criticality violation by tracking the dynamics of nuclear materials located inside a glovebox. Emerging technologies in sensing and virtual/augmented reality were combined with knowledge of nuclear criticality regulations to create a prototype Interactive Electronic Work Control System. Visual and depth sensors are used to detect the dynamically changing location of fissile materials in a glovebox during simulated working conditions. These measurements are then fed into a representative criticality safety model to determine appropriate separation distances between different materials. A visual depiction of these models is overlaid on representations of physical objects using virtual reality technologies to enhance the operator's perception of criticality safety regulations.

Keywords Glovebox • Augmented reality • Virtual reality • 3D sensing • Nuclear criticality safety

2.1 Introduction

2.1.1 Background

When a material needs to be isolated from the external environment, a sealed container called a glovebox is often used to perform necessary operations. Some materials require a controlled environment while others, such as radioactive materials, need to be isolated due to their potential to cause harm to personnel. The use of gloveboxes for operations involving nuclear materials is dictated by criticality safety regulations, which are an extensive set of rules written to ensure that all operations involving radioactive materials pose the smallest threat possible to technicians working in hazardous areas. A set of gloveboxes used at Los Alamos National Laboratory (LANL) is shown in Fig. 2.1 [1].

Although nuclear criticality safety regulations are written to ensure that glovebox operations are inherently safe, an additional, more stringent set of administrative criticality safety regulations exist to further ensure no harm comes to technicians working with hazardous materials. These administrative regulations control the proximity of different objects within a glovebox. Ensuring these regulations are followed is a tedious, costly process that often requires additional technicians devoted solely to overseeing and documenting each operation. Although manual observation and documentation is a functional method for enforcing administrative criticality safety regulations, a computerized approach has the potential to reduce violations. The proposed system, an Interactive Electronic Work Control System (IEWCS), would give operators a physical sense of radiation and criticality regulations to make them more aware of the invisible characteristics of the materials they are handling.

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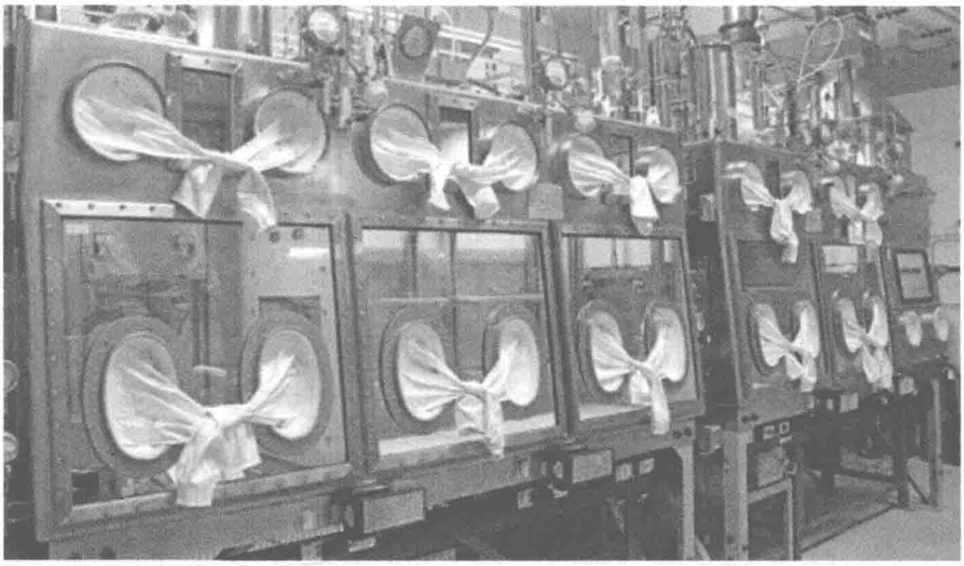

Fig. 2.1 Gloveboxes at Los Alamos National Laboratory

An important consideration in the development of the IEWCS is the method used to monitor activity in a glovebox. Monitoring could potentially be accomplished by the use of a 3D sensor that can track motion in real-time. The popularity of 3D sensors for motion gaming applications has enabled cost-effective 3D imaging to become widely accessible. Some of these sensors use infrared cameras to virtually reconstruct their surroundings and infer object positioning in 3D space. Creation of these reconstructions requires the detection of objects, assimilation of multiple images into a single point cloud, and visualization of inferred surfaces [2]. Research in this area has been applied to several fields, including marketing [3], rehabilitation [4], and industry [5]. Siemens has used this type of sensor for planning maintenance tasks in areas exposed to nuclear radiation. Operators simulate the motions necessary to complete specific jobs while being scanned by a Microsoft Kinect sensor. The operator's motions are saved and integrated into a model of the building that contains radiation hazard information to calculate the exposure that the operator would receive while performing the task. This process is repeated until the exposure is determined to be as low as reasonably achievable.

Finally, a method is needed to visualize information about a material's radioactivity. Augmented or virtual reality technologies are being considered for this application. Augmented reality (AR) is a layering of virtual information over real-world objects; it merges tangible reality with digital information [6]. Virtual reality (VR) is "the use of computer technology to create the effect of an interactive three-dimensional world in which the objects have a sense of spatial presence" [7]. While both AR and VR technologies were originally inspired by the gaming community, they have since been widely applied to scientific, industrial, and commercial research. In the medical field, surgeons have experimented with AR technology to overlay X-ray images onto the site of injury during operations [8]. Similarly, in industry, AR and VR products have been used to interactively guide workers through steps requiring detailed instructions, suggesting a potential to replace directive handbooks [9]. Researchers have also found a wide range of applications for AR and VR technologies in the nuclear industry. Hirotake [10] states that VR can reduce the time, expense, and danger associated with the education of nuclear power plant employees for both operations and maintenance training. Researchers at LANL have also used VR to examine the possibilities of deploying nuclear safeguard systems. A study completed by Michel [11] concluded that regulations and procedures related to nuclear criticality safety can be incorporated into a VR environment and used for design, planning, training and safety enforcement purposes.

2.1.2 Motivation

Although emerging technologies are currently being implemented in the nuclear field with promising results, continued research in their application to criticality safety is essential to determine if these technologies can contribute significantly to decreasing the number of administrative criticality safety violations in routine operations. Gloveboxes in particular have the potential to benefit from AR/VR technologies. Operators currently rely solely on personal knowledge and alertness to safeguard against administrative criticality violations, and experience has shown that many violations are either unnoticed or unreported. Although these violations do not result in safety hazards to personnel, their occurrence can cause costly facility shutdowns and lengthy policy re-evaluations. This research has the potential to reduce the number of administrative criticality