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MECHANICAL DESIGN AND VIBRO-ACOUSTIC TESTING OF ULTRATHIN CARBON FOILS FOR A SPACECRAFT INSTRUMENT

John D. Bernardin
Space Sciences & Applications Group
Los Alamos National Laboratory
P.O. Box 1663, MS D466
Los Alamos, NM USA 87545

Allen G. Baca
Satellite Mechanisms Group
Dept 2617
Sandia National Laboratory
Albuquerque, NM USA 87185-0521

ABSTRACT

IBEX-Hi is an electrostatic analyzer spacecraft instrument designed to measure the energy and flux distribution of energetic neutral atoms (ENAs) emanating from the interaction zone between the Earth's solar system and the Milky Way galaxy. A key element to this electro-optic instrument is an array of fourteen carbon foils that are used to ionize the ENAs. The foils are comprised of an ultrathin (50-100Å thick) layer of carbon suspended across the surface of an electroformed Nickel wire screen, which in turn is held taught by a metal frame holder. The electroformed orthogonal screen has square wire elements, 12.7 μm thick, with a pitch of 131.1 wires/cm. Each foil holder has an open aperture approximately 5 cm by 2.5 cm. Designing and implementing foil holders with such a large surface area has not been attempted for spaceflight in the past and has proven to be extremely challenging. The delicate carbon foils are subject to fatigue failure from the large acoustic and vibration loads that they will be exposed to during launch of the spacecraft. This paper describes the evolution of the foil holder design from previous space instrument applications to a flight-like IBEX-Hi prototype. Vibro-acoustic qualification tests of the IBEX-Hi prototype instrument and the resulting failure of several foils are summarized. This is followed by a discussion of iterative foil holder design modifications and laser vibrometer modal testing to support future fatigue failure analyses. The results of these activities indicate that there is no strong dependency of the natural frequencies or transmissibilities of the foils on the different foil holder and screen configurations. However, for all foil holder designs, the natural frequencies of the foils were observed to decrease noticeably from exposure to acoustic testing. These test results, when combined with foil holder assembly considerations, suggest that the welded frame and integrated screen designs should be incorporated into the architecture of the IBEX-Hi flight instrument.

INTRODUCTION

The IBEX-Hi spacecraft instrument, shown in Fig. 1, was designed for NASA's Interstellar Boundary Explorer (IBEX) Mission [1]. IBEX-Hi is an energetic neutral atom (ENA) imaging instrument that utilizes electro-optics to capture and analyze a high-energy spectrum of ENAs. A brief summary of the design features and functionality of the instrument is best described by referring to Fig. 1. At the donut-shaped entrance aperture of IBEX-Hi, particles attempt to enter and pass through a collimator. The collimator, consisting of a series of negatively and positively charged large aperture grids, repels background electrons and ions and permits ENAs from a narrow field of view to enter the instrument. Upon exiting the collimator, the ENAs pass through an ultrathin (50-100Å thick) carbon charge-conversion foil where the ENA is stripped of an electron, yielding a net positively charged ion. The metal frames supporting the carbon foils are positively charged so-as to accelerate the charged ions downstream into an electrostatic analyzer. This analyzer is formed from two concentric half-torroidal-shaped electrostatic analyzer (ESA) plates. An electrical field established between the two plates, helps direct the ions into a centralized detector section. The electric field imposed between the two ESA plates is selected so that only ions within a specific mass-energy band can pass through it. Once inside the detector, the ionized particles pass through a series of carbon foils, causing an emission of electrons. Positively-charged channel electron multipliers (CEMs) positioned on the side of the detector, collect the electrons and amplify the signal sufficiently so that it can be identified and recorded by the detector's electronics.

As discussed in [1] and [2], the mechanical design of the IBEX-Hi instrument proved to be quite challenging. Harsh environmental conditions imposed by the IBEX mission, combined with the need for delicate, high precision, and stable mechanical features, required that detailed structural and thermal analyses be combined with extensive environmental testing to qualify the mechanical design. In references [1] and [2], the mechanical design, thermal and structural analyses, and environmental testing of IBEX-Hi are discussed. In particular, reference [2] summarizes a set of random vibration and acoustic qualification tests of a prototype IBEX-Hi instrument. During those previous acoustic tests, several of the thin carbon charge conversion foils ruptured and failed. Several different foil holder design modifications were made to produce a design that could survive the acoustic environmental tests.

This present study focuses on the carbon foil holder design and utilizes empirical techniques in an attempt to describe the failure mechanisms experienced in the previous acoustic tests of reference [2]. First, the various carbon foil holder designs and previous acoustic tests are summarized. Next, an empirical, non-contact measurement technique to observe the resonance frequencies of ultrathin carbon foils before and after acoustic tests is provided. This data is used in part to select the final foil holder design and provide input to a future analytical approach that may predict the fatigue failure of the carbon foils.

Foil Holder Design

Figure 2 displays an exploded CAD view of a prototype IBEX-Hi instrument that was used for the environmental thermal, vibration, and acoustic tests of [1] and [2]. Of particular interest for this present study, is the foil holder assembly identified in Fig. 2 (one of fourteen in the prototype instrument) and presented in greater detail in Fig. 3.

The original baseline foil holder design consists of an electroformed Nickel screen (wire width = 12.7μm, thickness = 5.1μm, pitch = 131 wires/cm) stretched between two aluminum (Al-6061-T6) frames. A 0.25 cm high step on the lower frame allows the screen to be bent and stretched tight as the two frames are brought together with a complement of screws. Once the screen is stretched tight, a thin carbon film (50-100Å thick) is deposited onto the screen using the process described in [3]. The aluminum frame assembly is secured with screws to an electrically insulating Noryl (GN-30) cradle which in turn is mounted to the baseplate. The Noryl insulator is required because for electrically isolating the foil holder assembly from the baseplate.

This baseline foil holder design was integrated with a prototype instrument and subjected to an acoustic test early in the design of the IBEX-Hi instrument [4]. This testing resulted in catastrophic failure of several foils on the 0.25 cm high step frame, as displayed in Fig. 4. Removal and inspection of screens from foil holders that survived the acoustic tests, revealed significant plastic deformation and some small tearing of the screen material in the vicinity of the step in the lower frame. This lead to an intensive effort to review the design, fabrication, and assembly processes. Foil holder design modifications were performed that included shortening, tapering, and eliminating the screen stretching step in the lower frame, rounding the edges of the frame assembly that came in contact with the screen, adding a center support rib to the frame, and replacing the aluminum frame and fastener geometry with a stainless steel 304 version that was joined together with a series of spot welds (see Fig. 5).

Figure 6 displays screens that were previously stretched with aluminum frames of varying step heights, then removed from the frame assembly and pressed flat. The wrinkles in the screens show plastic deformation contour lines, which decrease in magnitude and density as the frame step height decreases. The flat frame obviously produces no permanent deformation of the screen material, although the holes that were punched in the screen for the fasteners, serve as significant stress concentrations.

To mitigate the stress concentration of the punched screw holes, a one-piece screen and border was fabricated with fastener holes in an electroforming process. This integrated screen and border design is shown alongside the traditional screen design in Figure 7. The wires in the screens are 12.7 μm (0.0005 in.) wide by 5μm (0.0002 in.) thick and are laid out with a linear density of 131 wires/cm.

Each of the different frame and screen designs mentioned above was included in several rounds of acoustic testing [2], the results of which are summarized in the next section. Prior to and following the last acoustic test of [2], the natural frequencies of the screens from various foil holder assemblies were measured using a non-contact laser vibrometer system. The remainder of this paper is dedicated to describing these non-contact frequency measurements and interpreting the empirical data to assess the mechanical robustness of the different foil holder and screen designs discussed previously.

Summary of Previous Acoustic Testing

In a previous investigation by the authors [2], a prototype IBEX-Hi instrument was fabricated, populated with various foil holder configurations, and subjected to several random vibration and acoustic tests. Figure 8 shows the environmental acoustic exposure profiles that were used in those tests. These profiles represent the qualification test levels that were derived, and later modified, for the IBEX mission and its corresponding spacecraft launch vehicle. In the Phase 1 acoustic test (reference Fig. 8), several frame geometries and screen configurations failed, similar to those shown previously in Fig. 4. Following these failures, it was concluded that the general foil design was inadequate, but also that the acoustic SPL test profile was overly conservative for the IBEX mission. In Phase 2 the acoustic profile was lowered (see Fig. 8) and the test was repeated with an assorted complement of foil holder and screen designs. None of the foils failed from the Phase 2 test. In Phase 3, a complete set of welded frame holders with a center rib (bottom picture is Fig. 5) were tested with both the traditional and integrated screen designs of Fig. 7. Following the Phase 3 test, it was discovered that two foil holders, one with a traditional screen, and one with an integrated screen, both suffered small 1 mm tears in their screens.

EXPERIMENTAL METHODS

In an attempt to understand, characterize, and predict the failure of the carbon foils during dynamic testing, resonant frequency measurements of the foils from several different holder configurations were measured. To achieve this, two Polytec Laser Doppler Vibrometers (OFV511/512 laser and OFV5000 controller) were used to measure the velocity spectrum of the resonating foil relative to the rigid foil holder frame which was secured to a vibration source. A B&K 4809 dynamic shaker, driven by a Krohn-Hite 7500 amplifier, was used to provide random low level vibration input to a single foil holder assembly over the frequency range of 10 to 2000 Hz. This equipment set-up is shown in Figure 9. The response data was used to construct transmissibility (ratio of foil response velocity to shaker input or reference velocity) versus frequency plots for each of the foil configurations shown in Table 1. This data was intended to be used as a relative comparison between foil holder designs to ascertain which design may be better suited for the dynamic environment, rather than an absolute pass/fail criteria.

Note that for the frames containing center ribs, dynamic response measurements were made in the center of both the left and right foils of the foil holder. For the frames without a center rib, measurements were made at the center of the foil. The reference laser was focused on the foil holder frame at the periphery of the foil. Preliminary tests were conducted to ensure that the foil holder frame was rigid relative to the dynamic shaker over the test input amplitude and frequency range.

For the data matrix of Table 1, all dynamic response measurements were made on foil holder assemblies that had survived a round of acoustic testing. Only for the cases of the welded frames with center ribs, were measurements made before and after acoustic testing. The data matrix was selected to assess the following foil holder characteristics on the dynamic response and survivability of the corresponding foils:

- Height of step on lower frame
- Presence of center rib
- Use of screws versus welding for assembling foil holder
- Traditional versus integrated screen design

RESULTS

TABLE 1. SUMMARY OF FOIL HOLDER AND SCREEN CONFIGURAITONS SUBJECTED TO LASER VIBROMETER FREQUENCY AND AMPLIFICATION MEASUREMENTS.

Frame Geometry	Center Rib?	Screen Type	Quantity Tested
0.25 cm step, screwed frame	**No**	**Traditional**	**2**
Flat screwed frame	**No**	**Traditional**	**2**
Welded frame	**No**	**Integrated**	**1**
Welded frame	**Yes**	**Traditional**	**4**
Welded frame	**Yes**	**Integrated**	**5**

Figure 10(a) shows a plot of frequency versus frequency mode number for the 0.25 cm stepped aluminum frame, the flat aluminum frame, and the welded stainless steel frame, all without the center support rib. Figure 10(b) displays the transmissibilities versus frequency for each of these foil holders. The vibration and acoustic test spectra of Fig. 8 show relatively high energy content in the vicinity of 50 Hz and 800 Hz, respectively. Consequently, to minimize the damage potential to the foils, it is desirable to have a foil holder design that possesses natural frequencies above 50 Hz, but either lower or higher than 800 Hz with relatively low transmissibilities in the neighborhood of 800 Hz. With this criteria, unfortunately, the data of Fig. 10 does not suggest one foil holder geometry is better than another. While there is a linear increase in frequency with mode number, there is no clear trend in transmissibility versus frequency for the five different foil holder configurations.

Figure 11 displays frequency and transmissibility data for the welded frame geometry with and without the center support rib and the inclusion of the integrated screen. The data for the welded frame with the center rib was selected from the mean of the five similar frames that were tested with that configuration. The frequency versus mode number plots are nearly identical for the two configurations, although the configuration with the rib appears to be stiffer with slightly higher frequencies. However, the transmissibility plots do not suggest a clear impact of the central rib in influencing the frequency response of the foil holder designs.

Figure 12 presents frequency versus mode number plots for welded frames possessing center ribs and traditional screens, with measurements being made before and after acoustic testing. Although the data is somewhat scattered, it appears that the natural frequencies of the foils are lowered as a result of the acoustic exposure testing. This reduction in frequency is consistent with loosening and wrinkling of the screen material as it is stretched plastically due to the acoustic loads, as reported in [2]. Figure 13 displays the transmissibility versus frequency for several of these foils from pre and post acoustic testing, but no clear change in this parameter is evident in the data.

Figure 14 displays the frequency versus mode number plots for welded frames possessing center ribs and integrated screens. The same type of behavior as reported for Figure 12 is evident here, a decrease in the natural frequencies as a result of the acoustic exposure testing.

CONCLUSIONS

This investigation focused on the design and associated noncontact dynamic response measurements of different holder configurations for ultrathin carbon foils. From the results of this study, the following conclusions can be drawn:

1. There is no strong dependency of the natural frequencies or transmissibilities of the foils on the different foil holder and screen configurations with the exception that the center

support rib tends to increase the natural frequencies a small amount.

2. Natural frequencies of the foils in the welded frame configuration with the center support rib, decreased noticeably after being exposed to the acoustic exposure testing of reference [2]. This was equally true for both the traditional and the integrated screen designs. No characteristic trend in the corresponding change of the transmissibilites could be observed.
3. The welded frame and integrated screen geometries greatly simplify the foil holder assembly configuration and assembly process. Since these design features are equal to or better than the other designs studied, from a dynamics response perspective, they should be incorporated in the foil holder configuration for the IBEX-Hi flight instrument.

Ongoing analytical studies are being performed to predict the fatigue failure of the ultrathin carbon foils given the acoustic loading profiles of Fig. 8, the foil failures reported in [2], and the frequency measurements reported in this study.

REFERENCES

[1] Jones, D. C. and Bernardin, J. D., 2007, “Thermal Modeling and Experimental Verification of the Interstellar Boundary Explorer’s High Energy Neutral Atom Imaging Instrument (IBEX-Hi),” *Proceedings to the AIAA Infotech@Aerospace 2007 Conference and Exhibit*, AIAA-2007-2949, Rohnert Park, CA.

[2] Bernardin, J.D. and Baca, A.G., 2009, “Mechanical Design and Dynamic Testing of the IBEX-Hi Electrostatic Analyzer Spacecraft Instrument,” *Proceedings to the 2009 AIAA Infotech@ Aerospace & AIAA Unmanned Unlimited Conference*, AIAA-2009-2025, Seattle, WA, 2009.

[3] McComas et al., 2004, “Ultrathin (~10 nm) Carbon Foils in Space Instrumentation,” Rev. Sci. Instr., 75(11), pp. 4863-4870.

[4] Baker, D. R., and Ramsey, M. J., 2004, “Intersteller Boundary Explorer-High Energy (IBEX-Hi) Flight Instrument Prototype Acoustic Test Report,” ATAC-23-15-82002101, ManTech Int. Corp., NASA Goddard Space Flight Center, Greenbelt, Maryland.

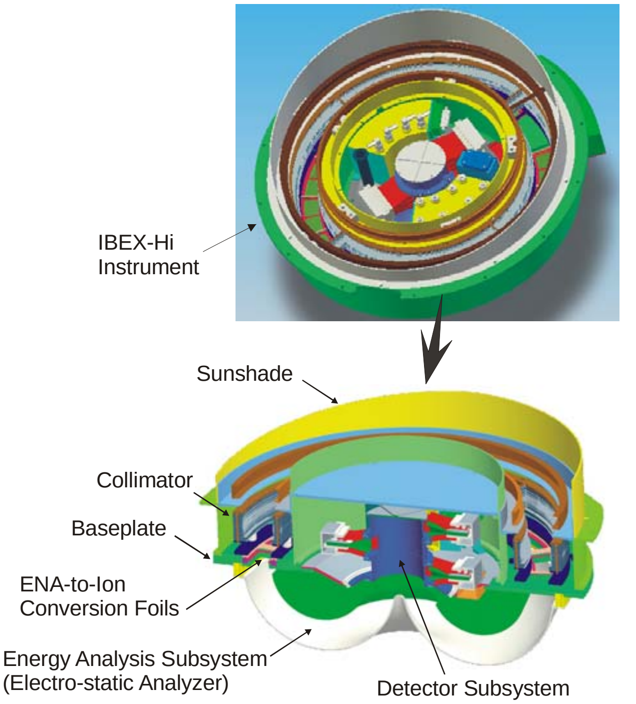


FIGURE 1. ISOMETRIC AND SECTION VIEWS OF THE IBEX-HI INSTRUMENT.

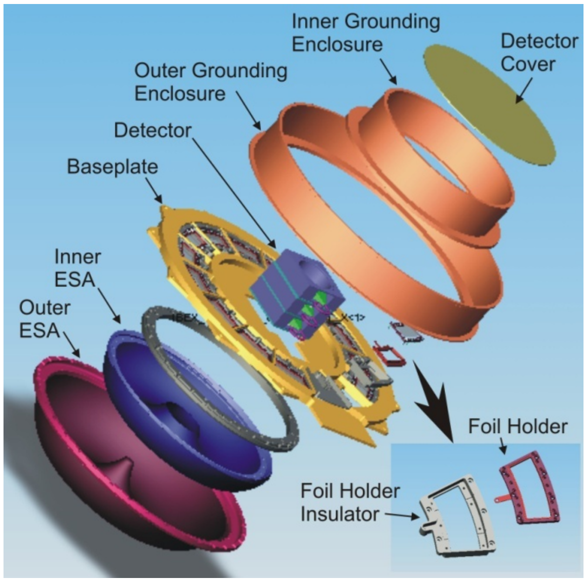


FIGURE 2. EXPLODED CAD VIEW OF THE IBEX-HI PROTOTYPE INSTRUMENT.

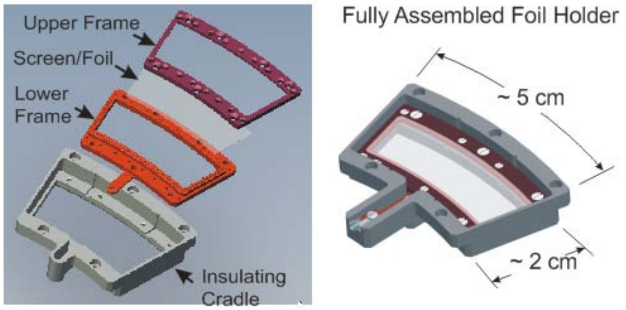


FIGURE 3. EXPLODED AND ASSEMBLED CAD MODEL VIEW.

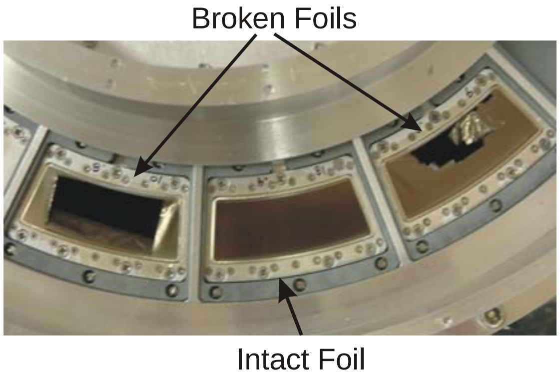
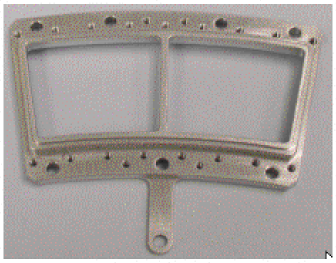
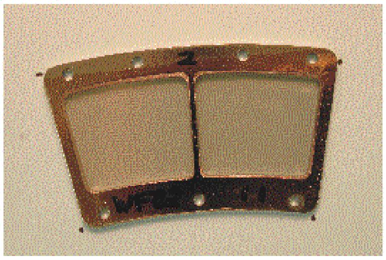


FIGURE 4. FAILURE OF TWO 0.25 CM STEP FOIL HOLDER FRAMES IN A PREVIOUS ACOUSTIC TEST [4].

Step Frame with Fasteners

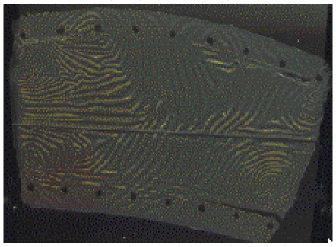


Step Frame with Center Rib & Fasteners

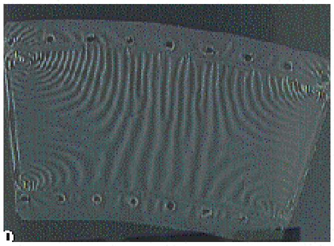


Welded Frame with Center Rib

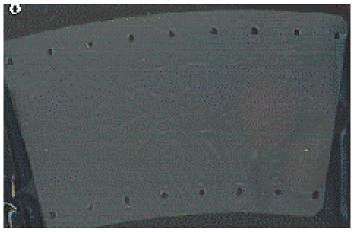
FIGURE 5. PHOTOGRAPHS SHOWING FOIL HOLDER ASSEMBLY EVOLUTION.



Stretched Screen from 0.25 cm Step Frame

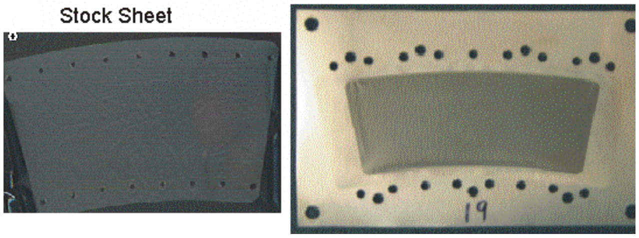


Stretched Screen from 0.08 cm Step Frame



Stretched Screen from Flat Frame

FIGURE 6. PHOTOGRAPHS OF SCREENS THAT WERE PREVIOUSLY STRETCHED ON DIFFERENT FRAME ASSEMBLIES, REMOVED FROM THE ASSEMBLIES, AND PRESSED FLAT.



Screen Cut from a Stock Sheet

Screen Fabricated in Electroforming Process

FIGURE 7. PHOTOGRAPHS OF AN ELECTROFORMED SCREEN CUT AND PUNCHED FROM SHEET STOCK AND A SCREEN WITH A BORDER FABRICATED IN AN ELECTROFORMING PROCESS.

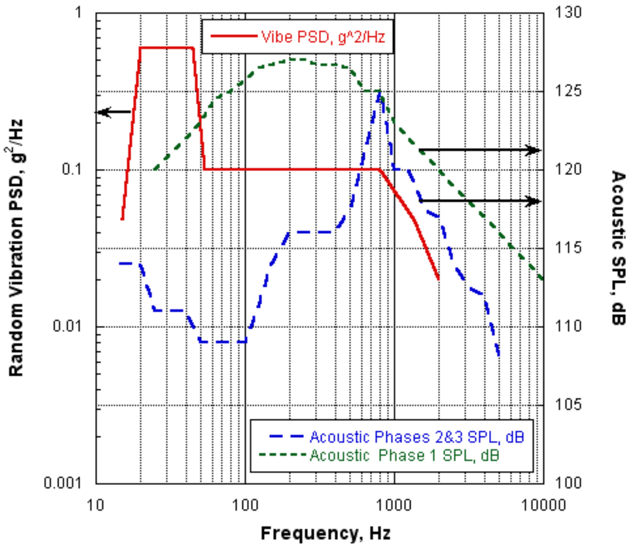


FIGURE 8. RANDOM VIBRATION POWER SPECTRAL DENSITY (G^2/HZ) AND ACOUSTIC TESTING SOUND PRESSURE LEVEL (DB) PROFILES USED IN DYNAMIC TESTING. INTEGRATED PSD AS WELL AS PHASE 1 AND PHASE 2/3 OVERALL SPL VALUES FOR THESE PROFILES ARE 12.3 G_{RMS}, 138 dB, AND 131 dB, RESPECTIVELY.

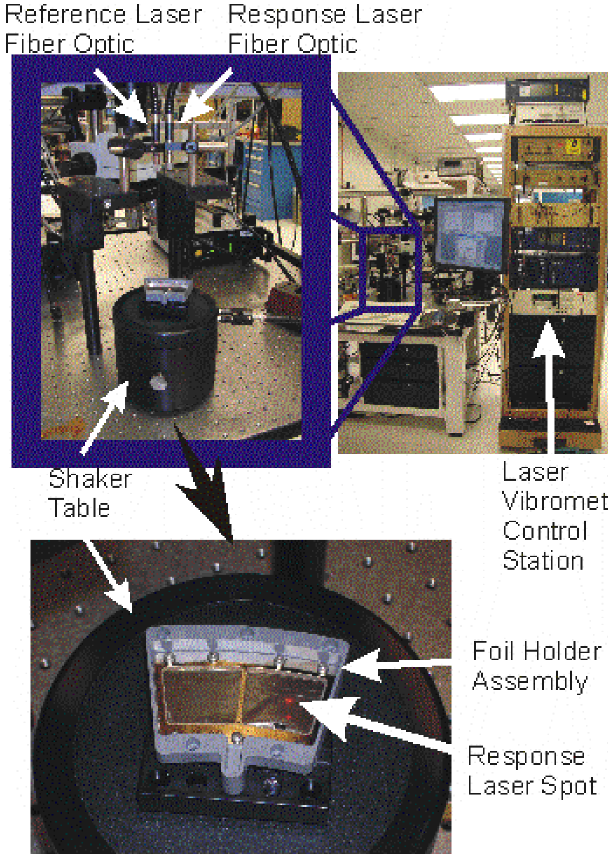
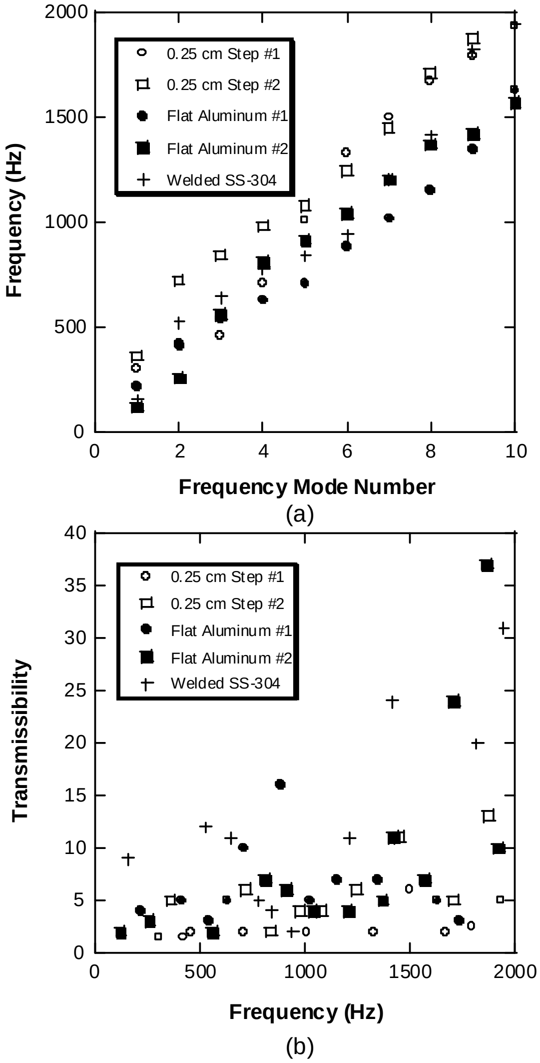


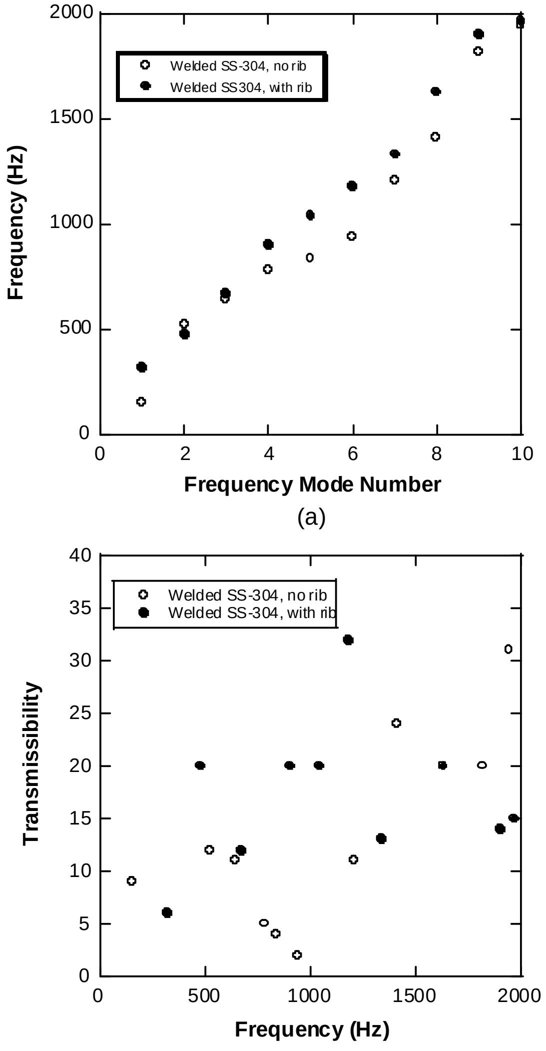
FIGURE 9. LASER VIBROMETER TEST STATION FOR MEASURING THE NATURAL FREQUENCIES OF VARIOUS FOIL HOLDERS.



(a)

(b)

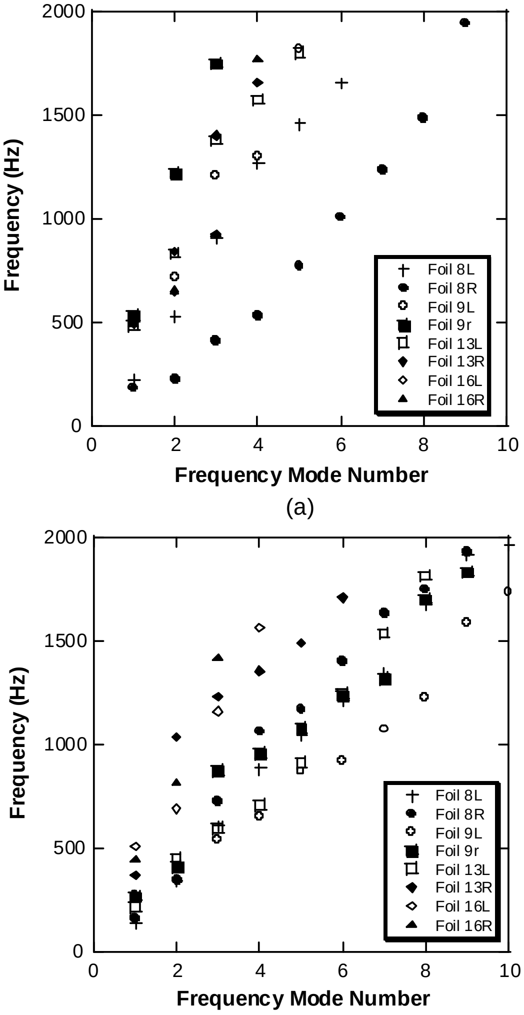
FIGURE 10. (a) FREQUENCY VERSUS MODE NUMBER AND TRANSMISSIBILITY VERSUS FREQUENCY FOR SEVERAL DIFFERENT FOIL HOLDER CONFIGURATIONS.



(a)

(b)

FIGURE 11. (a) FREQUENCY VERSUS MODE NUMBER AND TRANSMISSIBILITY VERSUS FREQUENCY FOR WELDED FRAME CONFIGURATIONS WITH AND WITHOUT A CENTER SUPPORT RIB.



(a)

(b)

FIGURE 12. FREQUENCY VERSUS MODE NUMBER FOR WELDED FRAME CONFIGURATIONS WITH A CENTER SUPPORT RIB AND TRADITIONAL SCREENS FOR (A) PRE AND (B) POST ACOUSTIC EXPOSURE TESTING.

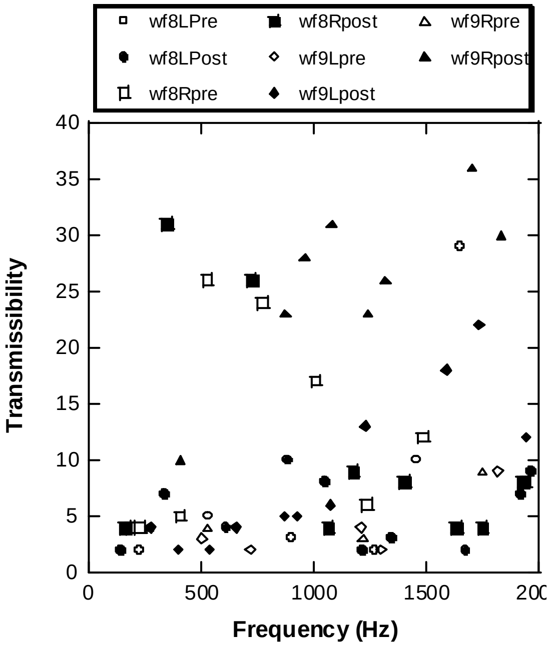


FIGURE 13. TRANSMISSIBILITY VERSUS FREQUENCY FOR WELDED FRAME CONFIGURATIONS WITH A CENTER SUPPORT RIB AND INTEGRATED SCREENS FOR PRE AND POST ACOUSTIC EXPOSURE TESTING.

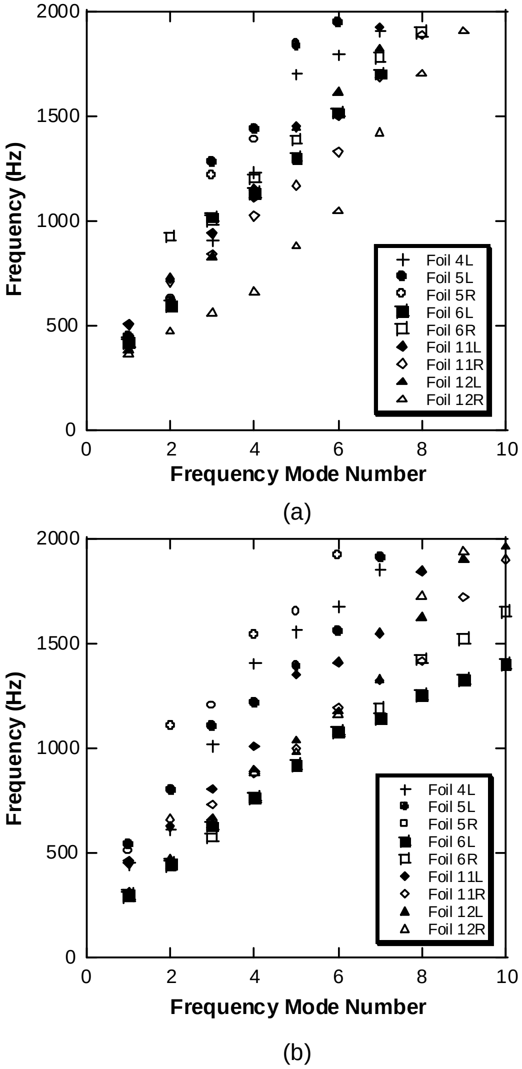


FIGURE 14. FREQUENCY VERSUS MODE NUMBER FOR WELDED FRAME CONFIGURATIONS WITH A CENTER SUPPORT RIB AND INTEGRATED SCREENS FOR (A) PRE AND (B) POST ACOUSTIC EXPOSURE TESTING.