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FEASIBILITY STUDY ON THE USE OF NON-CONTACT MEASUREMENT TECHNIQUES FOR MODAL TESTING OF A MEMBRANE STRUCTURE OF THE SBR SPACECRAFT

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TECHNICAL UNIVERSITY OF NOVA SCOTIA
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Executive Summary

The four month contract expiring on June 15, 1989 explored the feasibility of using various non-contacting measurement techniques for the modal testing of large membrane structures such as are expected to be found in the SBR spacecraft. The study covered both full-field and point measurement techniques.

(1) Full-Field Measurements

The full-field measurement techniques of holographic and laser speckle interferometry were ruled out immediately because of their extreme sensitivity and the fact that large vibration amplitudes were expected to be encountered during modal testing of the spacecraft structure. Moire fringe methods offered an acceptable measurement range and were explored in detail. The following methods were investigated:

(a) Shadow Moire
(b) Projected Grid Moire
(c) Projected Fringe Moire

A set of preliminary experiments were carried out on a stretched 1m x 2m membrane. Both large amplitude static and dynamic tests were conducted. Methods (a) and (b), which both use white light illumination, seem feasible for conducting relatively low cost qualitative studies of normal mode behaviour. Method (c) uses coherent light and would require either a very powerful laser or special observation cameras to generate a useable fringe display. To record and carry out quantitative fringe analyses for modal interpretation, particularly where the modal density is expected to be high, appears to be a laborious and time consuming procedure. There are no commercially available software packages which will automatically assign an order to each fringe and then analyse the results.

(2) Point Measurement Methods

There is some relatively new non-contacting point velocity measuring instrumentation on the commercial market which is based on measuring the doppler frequency shift of laser light reflected from a moving surface. One attractive feature of these instruments is their ability to measure large amplitude motions at standoff distances up to several meters. However, they are relatively expensive, ranging in price from $18,000 to $60,000 (Canadian). By using light beam-steering mechanisms with appropriate controllers, it appears feasible to sample a number of points on the structure at a rate far exceeding the expected periods of vibration. The authors have not had any hands-on experience with this class of instrumentation but did visit two companies which market competitive products for demonstrations. Without having access to one of these instruments, it has not been possible to explore their potential.

(3) Recommendations

It is recommended that:

1) A laser based vibrometer be purchased or leased to allow a thorough shakedown for use in carrying out modal analyses of the SBR structure.

2) A program be undertaken to develop hardware and software for rapidly scanning multiple measurement points on a test structure with such a device.

3) An image processing system consisting of a high quality video camera, digital frame grabber, supporting microcomputer and software be purchased to continue exploring the potential of the shadow and projected grid Moire methods for full-field dynamic-fringe recording.

In making these recommendations, it should be pointed out that the method of excitation to be used in the tests (as yet unknown) will probably restrict the use of one or more of the above mentioned methods or instruments. It would also be helpful if the type of structure and surface were known.

Dr. C.R. Hazell

Dr. A.K. Mitchell

June 15, 1989

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1. INTRODUCTION

This report describes work carried out under contract to the Directorate of Space Mechanics of the Communications Research Center in Ottawa, Canada for the purpose of evaluating potential non-contacting displacement measurement techniques for use in the modal testing of large membrane structures. The term 'membrane' is used in a general sense throughout the report to mean a relatively flat, lightweight panel with a low overall mass/stiffness ratio. Such structures are expected to make up a significant part of the proposed SBR spacecraft, although their form will not be known exactly until the design is finalized. A non-contacting measurement technique is desirable for modal testing such structures in order to avoid the mass loading effects of conventional accelerometers.

Each of the potentially viable non-contacting displacement measurement schemes identified in the interim report are discussed in detail in subsequent sections. These include the shadow and projected grid/fringe Moire methods, laser doppler vibrometers and fiber optic probes. One new commercial instrument, the laser proximity probe, has come to light during the study and has been included here for evaluation. Optical tracking systems such as those marketed by Optron and Zimmer have not been covered because another measurement system with similar performance capabilities and characteristics (Motion Analysis) is already being independently evaluated by DSM. Several methods already ruled out in the interim report are also ignored, such as holographic and Laser speckle interferometry.

2. MOIRE METHODS

2.1 General

Moire is a term used to describe the coarse fringes which sometimes appear when two similar images of fine line patterns are superimposed. The fringes are caused by minute differences in the pitch and/or inclination of the fine lines in the original images and may be used to accurately measure small full field deformations of either grid with respect to the other. A set of Moire fringes resulting from the superposition of straight line grids is shown in figure 2.1.

The Moire phenomenon has been used in several ways to study motion. Shadow Moire is perhaps the most common technique used for dynamic studies, but the projected grid and projected fringe methods are also well-known. Each method allows real-time fringes related to the instantaneous displacement of the surface under study to be observed as the object moves. The full-field displacement at any point in time can then be found from such a display by recording and later interpreting the position and number of fringes which appear.

Although these methods are well known in the literature, no commercial Moire-based measurement system is currently available. This section of the report is devoted to determining the viability of assembling such a system from scratch for large scale modal

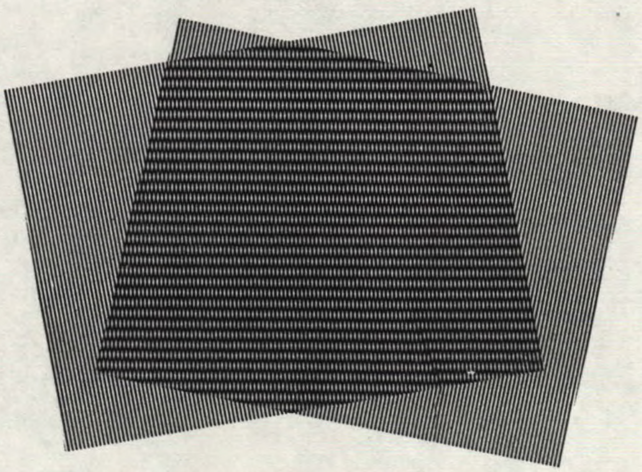


Figure 2.1. Moire fringes resulting from the superposition of two line grids.

testing. It would seem that the most challenging problem to be overcome in this regard relates to the recording and interpretation of dynamic moire fringes. Regardless of the fringe generation mechanism used, the 'live' fringe display observed during a test must be converted into a set of discrete point time-displacement records to obtain useful displacement information. To accomplish this it is necessary to record the position of the fringes as they move and conduct an after-the-fact analysis of the data. The methods used for the recording and reduction of test data are therefore very important in assessing the overall performance of a Moire measuring system.

2.2 Principals of Operation

2.2.1 Shadow Moire

Shadow Moire has historically been used to measure displacements several orders of magnitude smaller than are required for the SBR project. In this method a transparent/opaque line grid is held close to the surface of the object under study as shown in figure 2.2 and illuminated so as to cast shadows. The 'shadow grid' is then viewed by looking through the master grid, which causes dark Moire fringes to appear in real time whenever the solid grid

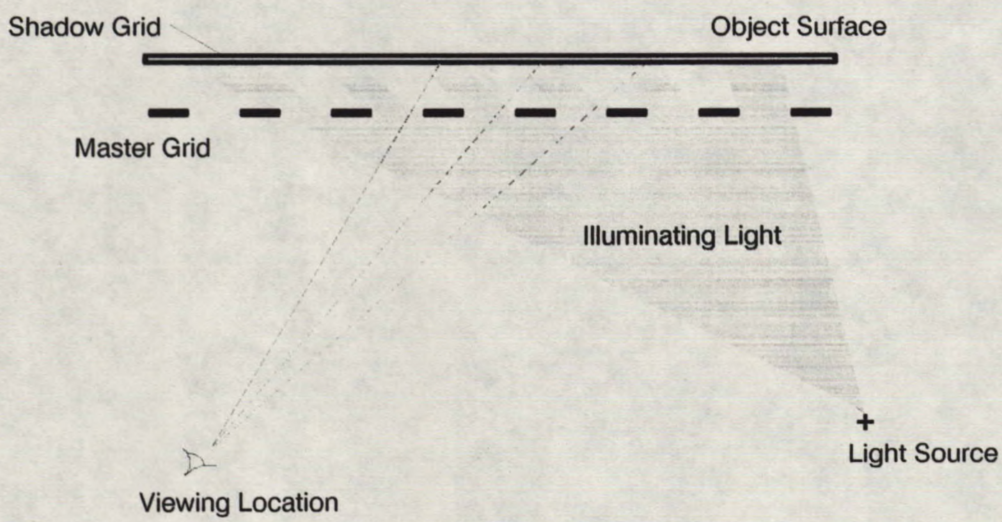


Figure 2.2. Schematic of a shadow Moire arrangement.

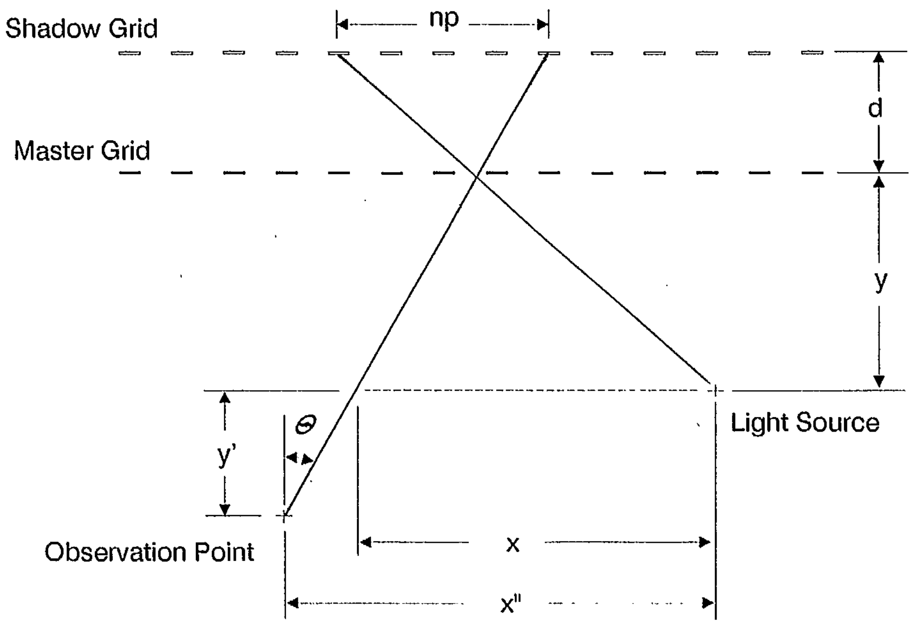


Figure 2.3. Terms important in the analysis of shadow Moire Fringes.

lines conceal the bright areas on the object. Conversely, the image appears bright whenever the shadow and master grids are shifted by an integral number of grid pitches relative to each other along a particular line of view. Conditions for the appearance of the bright and dark fringes can be predicted if the shape of the surface and the orientation of the motion are known. The analysis is greatly simplified by assuming the surface to be plane and the motion to be in a direction normal to this plane, as shown in figure 2.3. In this case, similar triangles can be used to predict that a bright fringe will occur whenever

$$np/d = x/y \qquad n = 0,1,2.... \tag{2.1}$$

where n is an integer describing the fringe order, p is the shadow grid pitch, d is the gap between the surface and the master grid and x and y are distances shown in the figure. The appearance of the dark fringes is just as simply predicted by replacing n with n+1/2.

Equation 2.1 can be used to determine the absolute position of a point in space if both the fringe order and position of the master grid are known, but this is not often the case in actual practice. It is generally only possible to calculate relative displacement differences between points in the same image by observing Moire fringes, and even then it is sometimes difficult to decide on the sense of the motion. A complication in the analysis is the fact that the fringe sensitivity is not necessarily everywhere constant, but instead can change as the quantity x in figure 3 varies across the field of view. The effect of this variation can be be included in the equation by simply replacing x with $x'' - y' \tan\theta$, where θ is the viewing angle to the surface. Whenever possible it makes sense to arrange the apparatus so that both the viewing and illuminating points are equal distances from the surface. When this happens y' becomes zero and equal amplitude fringes are observed everywhere over the field of view.

Diffraction of the illuminating light as it passes through the fine master grating is a major problem in the shadow Moire method. This diffracted light "bleeds" over into the dark areas of the shadow grid more and more as the surface moves away from the master grating, which reduces the contrast of the observed Moire fringes. This effect, which is always present to some degree, limits the usable measurement range which can be achieved. The diffraction problem can be lessened by using monochromatic, as opposed to white, light but never completely overcome. This in turn sometimes leads to air coupling problems between the (necessarily) relatively closely spaced moving object and the stationary master grid. As well, the size of object which can be studied is limited by difficulties involved in producing very large master gratings.

2.2.2 Projected Grid/Fringe Moire

In these techniques a line pattern is projected from a distance onto the surface to be studied, and an image of the scene brought to a focus with a lens. A pre-recorded photographic negative of the same scene in some reference position is placed in the focal plane of the lens, as shown in figure 2.4. Any light that passes through this negative 'filter' is used to form a visible image with the aid of either another lens system or a simple ground glass plate placed close to the negative. Dynamic Moire fringes are observed as the object moves.

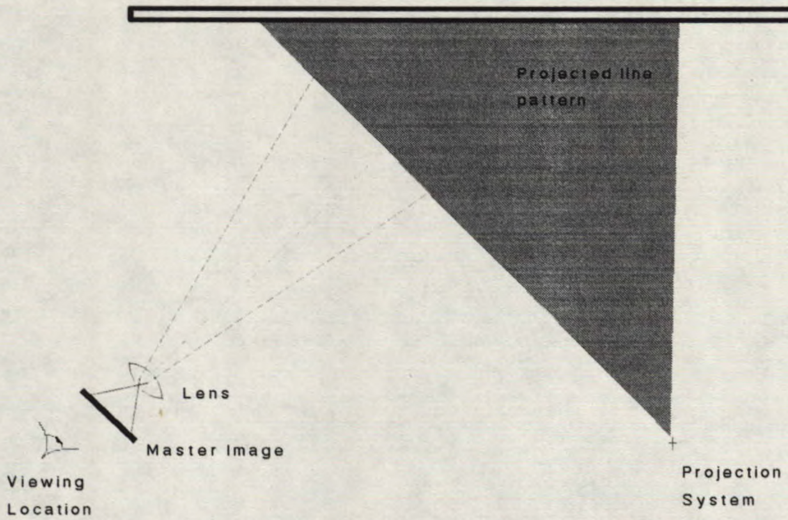


Figure 2.2.4 Projected grid/fringe Moire layout.

The fringes are analysed in exactly the same manner as those encountered with the shadow Moire arrangement except for the fact that a virtual reference image takes the place of the reference grid. Bright and dark fringes are again predicted using equation 2.1, and the arrangement can be made to yield constant amplitude fringes by simply placing both the illuminating light source and the observation point at equal distances from the subject. The two methods differ in the way that the line pattern is caused to appear. The simpler of the two is the projected grid technique, where a master image is projected on the moving surface in same manner as a slide projector works. The size and quality of the projected grid is a function of the diameter of the projection lens, the pitch of the master grid and the nature of the illuminating light source. Either white or monochromatic light can be used, but the latter gives better results. A potentially significant problem with projected grid systems involves the generally shallow depth of focus of the projected line image.

The projected fringe technique causes lines to appear as a result of interference between two coherent, collimated laser light beams. Fringe contrast is generally better than with the simpler scheme, depth of field is infinite and the grid pitch easily adjustable. Unfortunately the attainable grid size is limited to the diameter of the collimating optics, making the method useless for this application.

2.3 Interpretation of Test Results

The methods used to analyse Moire fringe patterns are very similar to those used in the analysis of holographic or photoelastic fringes. The process can be either extremely simple or moderately complex depending on the level of precision required in the results. The crudest approach is to simply count the fringes appearing on the image between any two points of interest, estimate the fractional fringe orders involved and then calculate the displacement difference based on this value. The expected error in such a measurement is on the order of one fringe order. More precise methods either attempt to determine the fractional fringe orders exactly or use curve fitting to determine the displacement profile over some larger area of the image.

The curve fitting method generally gives the most accurate results. In this method a grid of straight lines is laid out over the surface and the location and order of the fringes falling along each line are determined. The displacement is then calculated at each of these points and a smooth displacement curve drawn using cubic splines, Bezier curves or some other curve fitting algorithm. The fitted curves can then be used to very precisely determine displacements at arbitrary points along the line.

Although many attempts have been made at automating fringe analysis procedures for Moire, holographic and photoelastic applications none has been entirely successful. Almost all of these schemes rely at some stage on human input to establish the order of the fringes and therefore can not be considered truly automatic. To the best of the authors' knowledge, no system has ever been marketed for the analysis of dynamic fringes, which pose some special problems discussed in later sections of this report. For this reason it would seem impractical to use any of the commercial fringe analysis systems for this project.

2.4 Performance Evaluation

2.4.1 Introduction

Because no commercial Moire systems of any type are commercially available, it was necessary to carry out laboratory experiments to assess the limitations and relative performance characteristics of various fringe generation techniques. Of primary interest were the approximate coverage area, measurement range, sensitivity and physical layout size which could be expected with each while maintaining acceptable fringe quality. These trials, which are described in subsequent sections, were conducted using readily available and often non-optimum optical components and should be regarded as a starting point only in assessing the potential of the Moire methods.

During these tests it was also possible to assess the feasibility of using commercial video technology to record and study the dynamic Moire fringes which were generated. Dynamic recordings of certain tests were made using a portable Sony video camera and VCR, which were later digitized using a video frame grabber card manufactured by Redshift Limited. The results of this investigation are further discussed in section 2.4.4 under the heading of 'fringe recording systems'. Selected digitized frames from the videotape have been included in this section as illustrations, printed using the postscript halftoning facilities supported by the Apple LaserWriter.

A relatively large test structure was used for the tests in order to properly determine the area of coverage for each of the proposed fringe generation methods. This consisted of a 2m x 1m sheet of 1mm thick white vinyl stretched over a heavy steel frame, creating a planar structure with some characteristics similar to those of the SBR membranes. The experimental membrane is shown in figure 2.6.

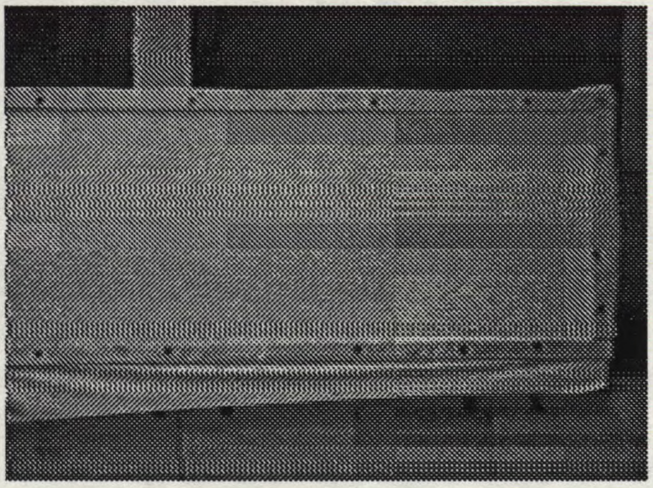


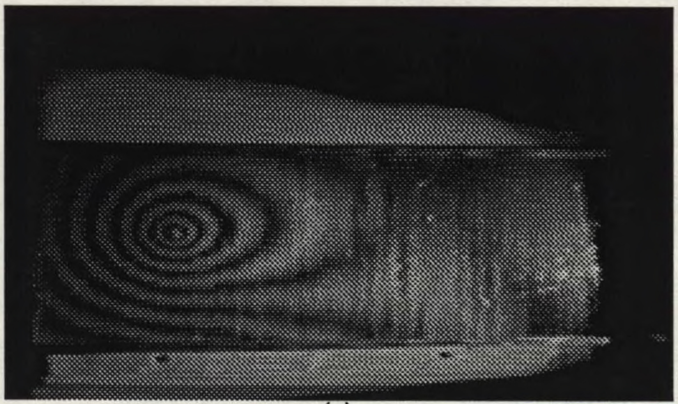
Figure 2.6. The experimental membrane structure.

2.4.2 Shadow Moire

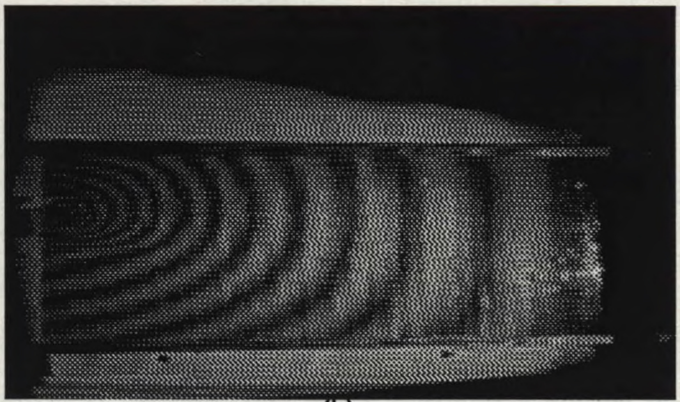
The shadow Moire approach was tested using a relatively coarse master grid, made by masking off 2 mm wide strips on a 1 m x 1/2 m sheet of clear plexiglass. The sheet was spray painted with black paint and the tape removed to create a 4 mm pitch master grid. This was mounted in an adjustable set of tracks which could be attached to the frame at different standoff distances from the membrane. Performance tests were conducted using both white light from a simple commercial slide projector and 514.5 nm coherent light from an argon laser to illuminate the master grid. Observation and illumination points were kept at the same distance from the membrane so that the observed fringes represented lines of constant deflection as discussed in section 2.2.1.

Excellent quality fringes were observed with this apparatus with either light source. The use of laser light significantly lengthened the acceptable standoff distance which could be achieved between the grid and membrane, but even the white light source allowed good quality fringes to be observed with gaps as large as one third of a meter or more. It would appear that the diffraction problems traditionally encountered in the shadow Moire method are greatly reduced when using such a coarse master grid. The total measurable range of a shadow Moire system is always the same as it's maximum standoff distance, which in this case would be more than adequate for the project at hand.

By varying the x and y dimensions in equation 2.1 it was possible to vary the observed fringe sensitivity over quite a wide range independently of the grid pitch. Grid sensitivities ranging from 2 to 50 mm/fringe were easily attained. By swinging one end of the master grid out from the plane of the membrane it was possible to introduce a set of static displacement fringes to the display which could be used to determine the sense of the membrane motion. These fringes represent a known DC component in the measured displacement, which can be subtracted away in any subsequent analysis. Shadow Moire fringes resulting from motions towards and away from the master grid are shown in figures 2.7 (a) and (b).



(a)

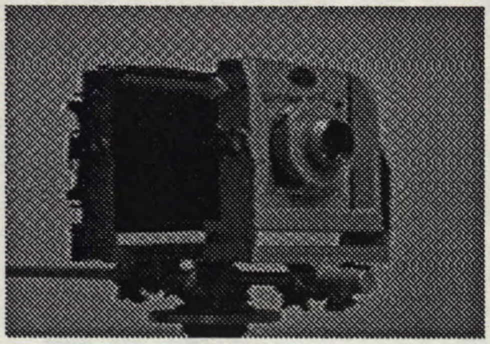


(b)

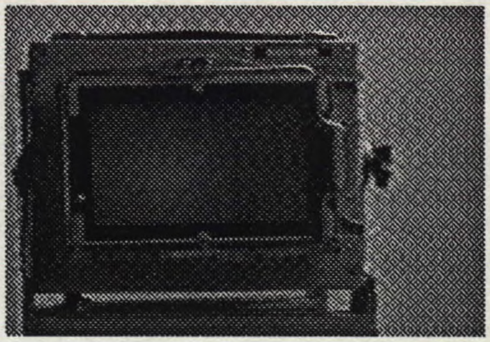
Figure 2.7. Moire fringes resulting from motion (a) towards and (b) away from the observer.

2.3.2 Projected Grid/Fringe Moire

Experiments were conducted to test the projected grid and projected fringe Moire methods using both white and coherent light. In each case the master image for the experiments was a photographic negative clamped in the image plane of the simple 4' x 5' box camera shown in figure 2.8 (a). The master images were recorded by focusing an image of the projected line pattern used for each test on the ground glass screen shown in figure 2.8 (b), then replacing it with an unexposed high contrast glass photographic plate. The plate was exposed and after processing was placed back in the focal plane of the camera to 'filter' the real-time image of the scene. Light passing through the filter was collected by a 125 mm diameter lens and directed to the video camera used to record the resulting dynamic Moire fringes.



(a)



(b)

Figure 2.8. The camera used in projection Moire tests.

The line images used in the experiments were projected in three different ways. In the simplest case a commercial 35 mm slide projector was used to cast a white light pattern on the surface of the membrane. High quality fringes which completely covered the membrane surface were observed with this setup so long as a sufficient standoff distance was used. The necessary standoff with the relativly low quality projector optics was approximatly 5 m. The projecter itself was normal to the plane of the membrane so that the projected grid would be of constant pitch. Brightness and contrast of the observed Moire fringes was not quite as good as with the shadow Moire arrangement, but were considered acceptable. Grids as fine as 0.5 lines/mm were projected, which resulted in Moire fringe sensitivities of 2 mm/fringe or more. Measurement range for the system was only limited by the depth of focus of the projected line grid, which was approximatly 1 meter over much of the membrane. A typical fringe display is shown in figure 2.9.

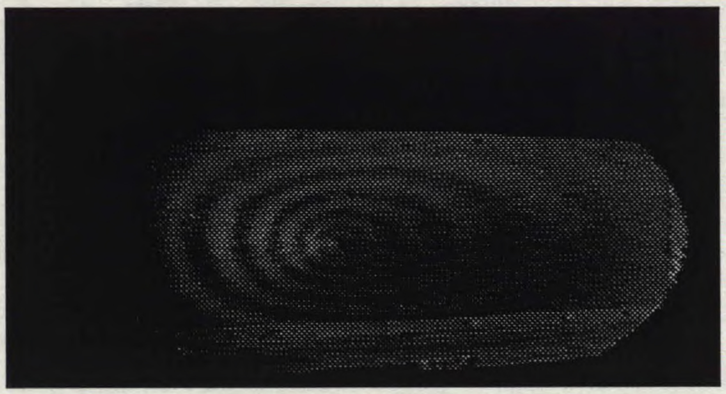


Figure 2.9. An example of white light projected grid Moire fringes.

Similar experiments were attempted using other projection lenses in an effort to reduce the substantial standoff required with the commercial slide projector. These were largely unsuccessful, always being limited in terms of the depth of focus and coverage area. Switching from white to coherent (laser) light significantly increased the depth of focus which could be achieved in the projected images. Coherent light with a 200 mm diameter projection lens allowed a excellent quality grid (covering the entire 1m x 2m membrane) to be projected from a standoff distance of less than 2 meters. The observed Moire fringe contrast was similar to that achieved with the white light scheme just described, but the overall illumination levels were too low to be recordable with the video equipment on hand.

A variation in the coherent light projected grid scheme was also tried which used collimatated laser light and spatial filtering of the resulting image to generate a projection grid with almost infinite depth of focus. The scheme, which would be more properly referred to as a projected fringe method, generated excellent contrast line patterns but wasted a significant portion of the laser's output. The Moire fringe display was even dimmer than with the simple projection technique and again could not be recorded by the video camera.

2.4.4 Fringe Recording Systems

The recording system used to capture the dynamic Moire fringe display should ideally provide a continuous record of the instantaneous position of the dynamic Moire fringes. The most cost effective recording methods appear to be commercial video or movie cameras, which both limit the frequency bandwidth and spatial resolution of the subsequent FFT analysis to some extent. Of the two, Video is more restricted in terms of resolution and sampling rate but can be conveniently digitized for analysis. It also would allow real-time remote monitoring of tests from outside the vacuum chamber whereas film would not. For these reasons, video is seen as being more feasible than film for this project. Some aspects of its performance were tested by using a commercial video system to record the experimental test results.

The performance of the system was assessed by conducting steady-state vibration tests on the membrane, recording the moving fringe display and then digitizing individual video frames. The digitization was carried out using a frame grabber card manufactured by

RedShift Ltd., which created an image with a 192 x 256 pixel resolution and 256 gray levels. These images could then be easily scanned to determine the location of the bright and dark fringes if desired.

The steady state vibrations were excited using a large B+K electromagnetic shaker attached to the membrane via a magnetic mount. The shaker could produce a vibration amplitude as large as 25 mm peak-to-peak at frequencies as low as one Hertz. Significant problems were noted when trying to record fringe displays oscillating at frequencies greater than 3-4 Hertz with the video set-up. These problems were thought to be inherent in the nature of the recording medium, and are discussed in the next section.

2.4.5 Performance With Respect to the Critical Criteria

Putting aside the problems of recording and interpreting the fringes for a moment, it is conceivable that a Moire based measuring system could satisfy all of the critical criteria for this project. Acceptable resolution and measurement range can be achieved with either of the fringe generation schemes tested. Repositioning a single set of equipment between tests would not be a problem in the shadow Moire method, but would require substantial time and effort with a projection scheme. In either case the test equipment would be inexpensive enough to make multiple static setups feasible. Calibration is not a problem, and actual testing time in the vacuum chamber need be no longer than with a conventional accelerometer based system.

The most significant problem to be overcome in setting up a practical Moire measurment system lies in recording and interpreting the test results. From a recording standpoint, the standard video frame rate of 30 cycles per second would appear to limit the frequency bandwidth of a video-based system to something less than 15 Hertz. However, a video image actually consists of two separate 252 scan line images superimposed on each other using a technique known as interlacing. The interlaced images are drawn in alternating scan lines on the monitor, and updated at a rate of 60 individual frames per second. Provided the interlaced images could be separated at some point in the analysis phase, it might still be possible for a video based test system to satisfy the technical requirements. In any case the time and effort required to operate such a system would be enormous, and should not be underestimated. Consider that a 0.01 Hz. resolution FFT requires a time record at least 100 seconds long. Providing such a record requires the analysis of over 6000 individual video frames, if the desired 0-30 Hz. analysis bandwidth is to be preserved. Although a Moire scheme might be workable, it cannot be thought of as particularly attractive in this light.

Further complications arise in the actual analysis of the recorded fringes because of the the fact that even separated video images cannot be considered as instantaneous 'snapshots' of the dynamic scene. Significant amounts of time elapse between the recording of the individual scan lines in the image, which means that curve fitting should only be carried in a horizontal plane where the data can be considered more or less instantaneous. This rules out the use of commercial fringe analysis packages, which are all designed for the analysis of static images.

2.5 Development Required for Implementation

To implement a Moire system, it would first be necessary to develop a system to record and analyse the dynamic fringes. This would require developing software that would facilitate the analysis of the fringe patterns and construct the required time records at arbitrary spatial locations. The process could be more-or-less automated except for the actual assigning of fringe orders in each frame, which should be carried out manually. Some form of 'point and click' mouse based routine would be most appropriate for this purpose. Software development is not seen as a major obstacle to implementation.

2.6 Estimated Costs

A Moire-based measuring system would be relatively inexpensive to set up. The large, relatively coarse master grids and supporting frames required for the shadow technique could be easily constructed from commonly available materials at CRC, while commercially available projectors and cameras could be used to make up a white-light projected grid system. The major cost item in either ststem would be the video recording and analysis equipment. The video camera would have to be of the CCD type for use in the vacuum chamber, and would cost between $800 - $2200. A video frame grabber with at least 504 line resolution would be required to hope to separate the interlaced images. These range in price from $700 to $5000 exclusive of the necessary supporting computer and software. Prices for a representative image processing system are as follows:

Cohu CCD video camera	$ 2,100
Strawberry Tree VFG-512-8B image processing card	$ 2,233
Provision Software for above	$ 693
AT style Personal Computer with hard disk	$ 3,500
VCR and Monitor	$ 800

Total	$ 9,326

Technical specifications for the camera and image processing card are given in Appendix A.

3. Point Measurement Techniques

3.1 Introduction

The Space Borne Radar Contract Interim Report dated March 31, 1989 referred to two types of point measurement devices that warranted further study, i.e.:

(a) Fiber Optic probes

(b) Laser Doppler Vibrometers

Since that time another promising non-contacting point measurement device, the Laser Proximeter, has come to light. These three types of instrument are discussed in detail in this section of the report. The Laser Doppler vibrometers are dealt with first, since they seem to be the most promising of the group. The Laser Proximeter is included even though it was not possible to obtain a demonstration of it's capabilities during the study period. It is nonetheless an extremely interesting device. The fiber optic probes do not meet all of the critical criteria, but are included because of their simplicity and low cost. It is felt that they might still prove to be useful for at least part of the project.

Four laser based vibrometer units are commercially available which, on paper at least, have the potential to meet or exceed the technical requirements. All of these units are new to the market and to the best of the authors' knowledge only one or two of the four varieties have so far appeared in Canada. One of these, marketed by Ometron, has already been ruled out for this application in the Interim Report. Although every effort was made to obtain hands-on experience with each of the remaining three units, we were only able to obtain show-room demonstrations of the Polytec and Dantec instruments. The demonstrations of the Dantec unit took place in their sales office at Allendale, N.J., U.S.A., while the Polytec unit was shown to us in Montreal, Canada. All four of the units are actually manufactured in Europe.

There are two important difficulties in making definitive recommendations concerning equipment at this time. Firstly, the method of excitation to be used in testing the SBR components is still unknown, and secondly, the configuration of the structure itself has not yet been defined. These two difficulties are, of course, closely related. Is the excitation to be steady-state or transient? If transient, how repeatable will it be and what length of time record is required? Keeping these qualifiers in mind, each of the laser based vibrometers will be discussed with respect to (1) principal of operation, (2) performance with respect to the critical criteria, (3) development required for future implementation, and (4) estimated cost of implementation.

3.2 Polytec Fiber Optic Laser Vibrometer

This unit is marketed by Polytec Optronics Inc. of Costa Mesa, California in the U.S.A. and Optikon in Canada. Optikon is located in Waterloo, Ontario. The unit itself is manufactured by PolyTec GmbH of West Germany.

3.2.1 Principal of Operation

The fiber optic vibrometer, shown schematically in Fig. 3.1, is built around a Mach-Zender interferometer. Light from a continuous wave laser is split by beamsplitter BS1 into two beams, each of which travels through a different leg of the interferometer. The light emerging from the polarizing beamsplitter PBS1 is linearly polarized parallel to the plane of the figure. PBS2 also produces a plane polarized beam which travels to a second measuring head for differential measurements. The diverging laser light exiting the optical fiber in each

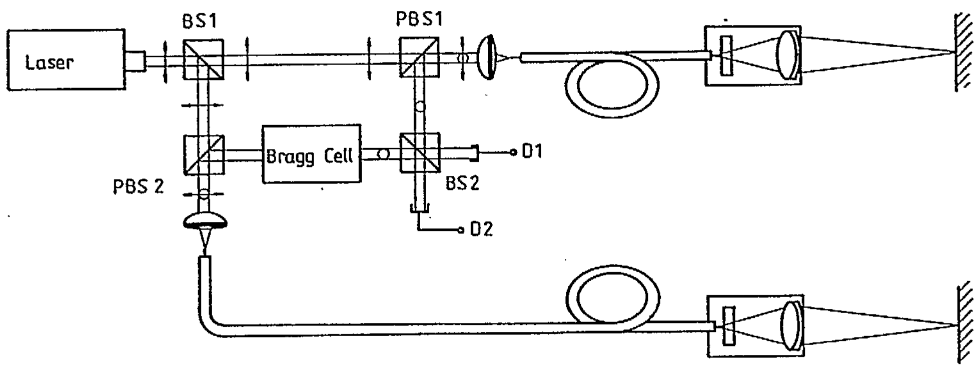


Figure 3.1. Schematic of the fiber optic vibrometer.

optical head is focused by a lens system onto the surface to be examined. The back scattered light, which contains the important information relating to the surface motion, is collected by the same optical heads and recoupled into their respective fibers. The fact that a single lens acts as both transmitter and receiver in each optical head eliminates the need for alignment. The quarter wave plate in front of the collecting optics flips the polarization of captured light perpendicular to the plane of the figure, so that the outgoing light can be separated from the incoming at the polarizing beamsplitters. The incoming signal light from both legs is reflected at PBS1 and PBS2 so as to interfere with each other after passing through BS2. The intensity modulation in the interference pattern detected at D1 and D2 contains the vibration information. The light scattering off the vibrating surface experiences a doppler frequency shift f_d, which is linearly dependant on the component of the velocity v of the surface along the direction of the laser light, according to the formula

$$f_d = 2v/\lambda \tag{3.1}$$

where λ is the wavelength of the laser. For a helium-neon laser with a wavelength of 0.6328 μm, f_d = 3.16 MHz/(m/s).

In order for the instrument to distinguish between forward and backward moving surfaces, an acousto-optic modulator in one arm of the interferometer introduces a constant 40 MHz frequency shift to the back scattered light. This shift essentially represents a velocity bias of about 12.6 m/s. using the above formula. Thus when the frequency shifted beam combines with the unshifted component, the intensity pattern registered by the detector cycles with a frequency of 40 MHz. even when no vibration is occurring. In the presence of vibration, the Doppler shifted signal frequency-modulates the 40 MHz. carrier. The signal processor demodulates the detector signal and retrieves the vibration information in the form of a signal proportional to the velocity of the moving surface.

3.2.2 Performance with Respect to Critical Criteria

Although the fiber optic vibrometer is designed to measure relatively high frequency, low amplitude vibration, the unit can be purchased with a combined amplitude/ velocity demodulator which might be useful for this application. When the velocity of the vibrating surface becomes too low for velocity demodulation (typical of low frequency vibrations) the

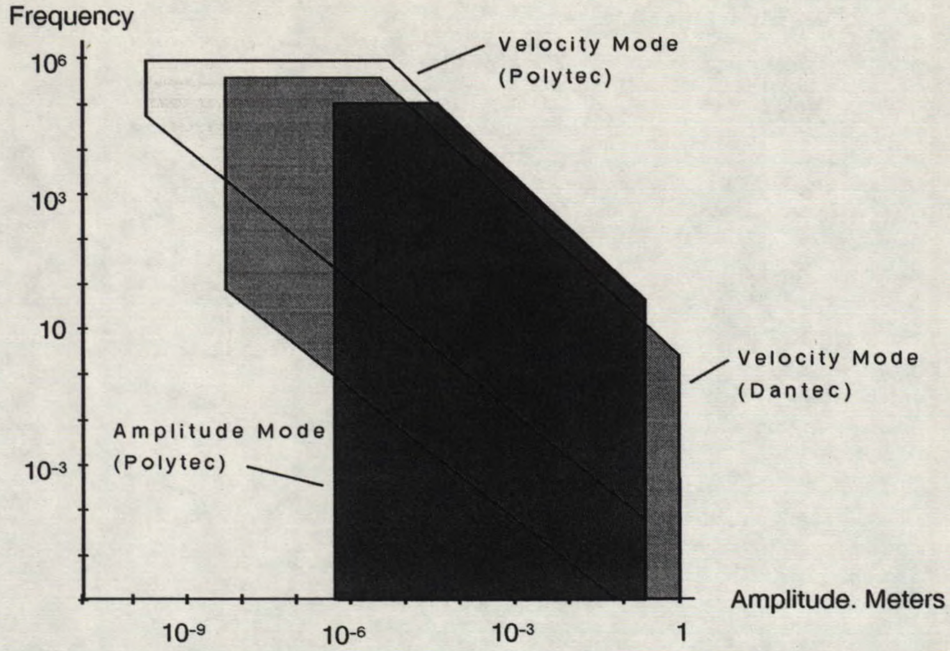


Figure 3.2. Performance nomogram for the fiber optic vibrometer.

amplitude demodulator can be used to track the position of the surface using a fringe-counting technique. According to the nomogram shown in Fig 3.2, amplitudes of up to 10 cm at frequencies down to DC are possible.

The output of the vibrometer using either demodulator is an analog voltage ranging from -10 to +10 volts, and the device has an excellent dynamic range of over 160 dB. Response time is rated at 170 ns with a step-function velocity change of 10 m/s. The standoff distance of the measurement head from the surface depends on the choice of optics attached to the fiber optic cables. A range of choices are available allowing standoff distances up to several meters.

Concerning the positioning of the measuring system, a very attractive feature of the fiber optic vibrometer is the fact that the measuring head(s) (which will probably be inside the chamber) are connected to the signal processing equipment via flexible fiber optic cables of varying lengths. This means that the heads can be easily moved about within the vacuum chamber to accommodate almost any size and shape of test structure. It also would seem possible to locate the processor outside the chamber and still make measurements inside over the flexible cables.

It is important to note that the fiber optic vibrometer only measures velocity (or amplitude) at a single measurement point at any given time. In order to establish mode shapes with only a single measuring point, the structure itself would have to be excited at a number of different locations. This could occur either sequentially or simultaneously depending on the method of excitation used.

Alternately, single point excitation could be employed along with multiple measurement points. This would require one of the following four schemes:

- **(a)** one complete vibrometer for each measurement point.
- **(b)** one processor with many measurement heads connected through a solid state or mechanical switching device.
- **(c)** One vibrometer with a steerable and/or translating measuring head which could scan predetermined points on the structure
- **(d)** one vibrometer with a fixed measurement head and remotely controlled mirrors steering the beam to predetermined points.

Of these, option (a) is the most attractive from a technical point of view. Each instrument could simply take the place of an accelerometer/charge amplifier set in a conventional modal analysis setup. Such a scheme would be prohibitively expensive. The initial response from the instrument's distributor when questioned about options (b), (c), and (d) was that the development costs of such systems would probably exceed the cost of several complete vibrometers. The authors are not convinced that this is necessarily so. These systems would be especially attractive if some form of steady-state excitation were ultimately chosen for the SBR modal testing.

The fiber optic vibrometer ordinarily needs no special calibration as the measuring head is moved from point to point on the structure. This means that it would be a relatively simple task to remotely relocate the measuring point between tests, for instance.

The head must capture a certain amount of backscattered light before the unit will operate, and the intensity of the available reflected signal is automatically monitored by the processor. A front panel display is provided which gives a visual warning when the signal strength falls below the critical point for proper operation.

As well being suitably reflective, the surface under study must fall within the depth of focus of the particular lens fitted to the measuring head. Units are available which give a usable measuring range on the order of several meters. This also constitutes the maximum possible standoff distance which could be used between head and surface.

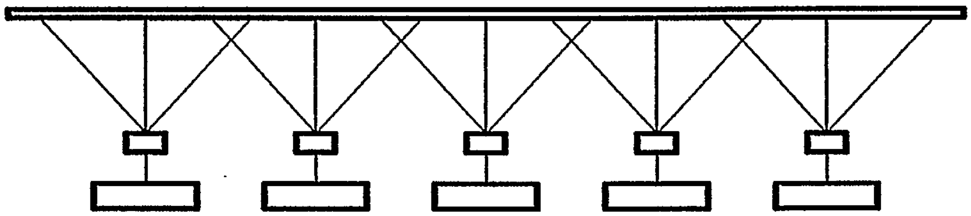
The resolution of the fiber optic vibrometer is less than one nanometer of amplitude when used in the velocity demodulation mode and one half the wavelength of helium neon laser light (316.5 nm) when used in amplitude mode. This absolute accuracy obviously far exceeds the technical requirements for this project. Spatial resolution is equal to the focused laser spot size on the surface, which is less than one millimeter when the instrument is positioned properly. However, adding a steering or pointing system to position the beam remotely during tests will alter the spatial resolution of the measurement system.

The instrument lends itself well to vibration measurements on two and three dimensional structures because of the flexibility of the fiber optic cables and its ease of positioning. However, it is only capable of measuring a single component of motion along the beam axis at any one time. Therefore, if the sense of a motion is unknown two or possibly three observations from different directions might be required to determine it. Conversely, if the orientation of the motion is already known a single vibrometer measurement from any observation angle determines both the amplitude and phase accurately.

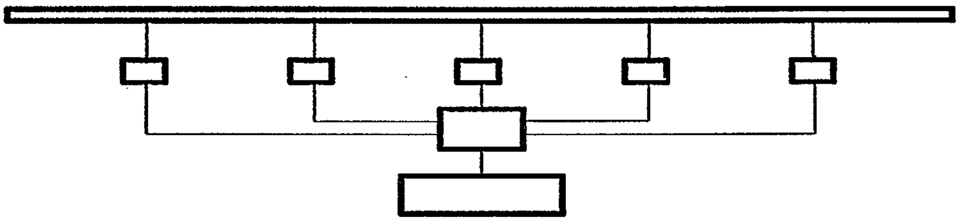
At this point it is difficult to comment on the required testing time since the nature of the structure and type of test are unknown. Testing time with this instrument should be no longer than that required for conventional accelerometers. The technical specifications for the fiber optic vibrometer are given in Appendix B.

3.2.3 <u>Development Required for Implementation</u>

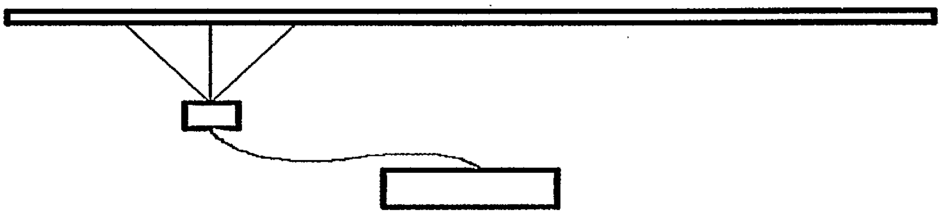
To develop the fiber optic vibrometer as a measurement system for this project would first require the acquisition of an instrument for testing with it's accompanying model 1100 velocity/amplitude demodulator. There is a good possibility that the instrument could be initially leased for this purpose. Once the instrument's capabilities are determined it would be much easier to assess the feasibility of developing one of the measurement schemes described earlier. Schemes (b), (c), and (d) would all require substantial development time and costs. The four possible approaches are shown schematically in figure 3.3. In all cases the measurement head(s) would be located inside the vacuum chamber with the processor outside.



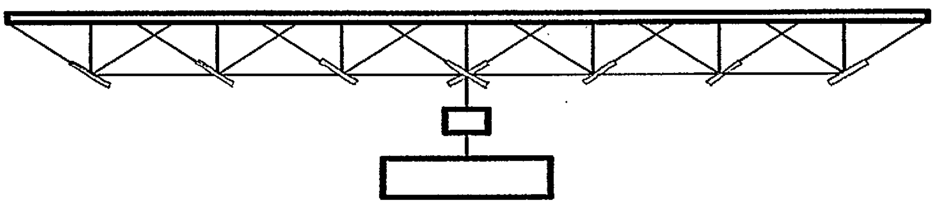
(a) Multiple measuring units



(b) Single unit with multiplexer



(c) Single unit with translating/ rotating head



(d) Single unit with mirror scanning setup

Figure 3.3. Possible measurement schemes using the fiber optic vibrometer.

3.2.4. Estimated Cost of Implementation

The cost of the basic fiber optic laser vibrometer, consisting of the OFV-1100 signal processor providing both amplitude and velocity measurements and two OFV-200 measuring heads with associated fiber optic connecting cables is approximately $60,000 Cdn.. The standard fiber optic cables are five meters in length. Additional costs would be incurred for longer cables.

The estimated capital cost of scheme (a) would therefore be approximately $60,000 for each measurement point required. As mentioned earlier, this seems prohibitive. The cost of implementing any of schemes (b), (c), or (d) are difficult to estimate at this time. Further study, preferably including some hands on experience with the fiber optic vibrometer itself, would be required before a practical and cost effective choice could be made.

3.3 Dantec 55x Laser Doppler Vibrometer System

This unit is marketed in the U.S. by Dantec electronics, Inc. (formerly DISA Corp.) of Allendale, N.J.. The unit is manufactured in Denmark by Dantec.

3.3.1 Principal of Operation

The principal of operation for this unit is very similar to that of the Fiber Optic Vibrometer discussed in the previous section, using the doppler shift of backscattered laser light from a moving surface to measure velocity. The surface must be diffusely reflecting, and the output is an analog voltage signal proportional to the (nearly) instantaneous velocity of the subject. The unit differs from the fiber optic unit in that the manufacturers claim that velocities as low as 10^{-6} m/s can be detected (essentially giving adequate performance at frequencies approaching DC), so that a special amplitude demodulator is not needed. The frequency vs. amplitude nomogram for this unit is also in Fig. 3.2. Note that the maximum amplitude range extends to 1 meter over the frequency range of 0.5 to 10^{-6} Hz..

Two other major differences between the units are the price and the fact that the 55x uses no fiber optic cables in its measuring legs. The Dantec unit retails for approximately $40,000 vs. $60,000 for the Polytec instrument, and is essentially one compact unit with the measuring head rigidly attached to the interferometer unit and laser. A schematic of this

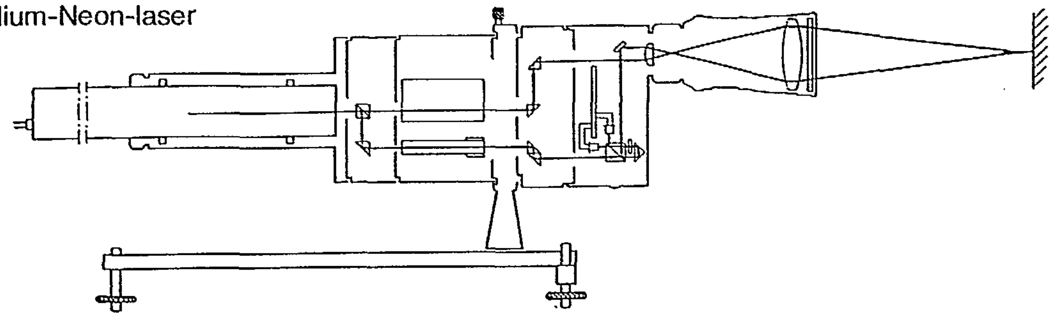


Figure 3.4. The Dantec Laser Doppler Vibrometer system.

arrangement is shown in Fig. 3.4. This means that the entire unit, laser and all, would most likely be mounted inside the vacuum chamber. A special pressure vessel would probably have to be built to house at least the laser, since it's helium-neon tube cannot be subjected to vacuum without rupturing.

3.3.2 Performance with Respect to Critical Criteria

The technical specifications of the 55x Laser Doppler vibrometer are shown in Appendix C. The amplitude and frequency requirements are well within the required criteria. The standoff distance ranges from 1.2 m to 20 m, depending on the choice of optics ordered. Concerning the positioning of the vibrometer system, much of the discussion which accompanied the Polytec Fiber Optic Vibrometer is again applicable here. For multiple point measurements, using one complete unit at each measurement point (measurement scheme (a) in section 3.2) is again a possibility. Schemes (b) and (c) are not possible because of the design of the unit. Scheme (d) is possible, but either the laser beam would have to be launched through a port to the steerable mirror or the entire unit would have to be enclosed in a pressure vessel inside the chamber to avoid exposing the laser tube to vacuum.

Again calibration and spatial resolution are not seen as problems in this application. Of course, the setup must ensure that a sufficient amount of backscattered light is captured by the collecting optics for the unit to function.

3.3.3 Required development for Implementation

Since schemes (b) and (c) are not possible with the 55x system, the steerable mirror arrangement is seen as the only possible way of scanning the structure during modal testing. A schematic of this system is shown in Fig. 3.5. The test structure will be multi-dimensional, which requires that a three dimensional mirror arrangement be employed to steer the various beams to their measurement locations.

Another option would be to implement a variation on scheme (b) where the entire vibrometer would be translated from point to point either during or between tests. Such multiple tests would require more vacuum chamber time and still require the development of a remote manipulator system. They also allow the possibility of errors to creep into the analysis due to changing environmental conditions between trials. Continuous, slow scanning by translating the entire unit during tests would only be appropriate if steady-state excitation is to be used, and may prove impractical in any case due to the delicate nature of the interferometer optics.

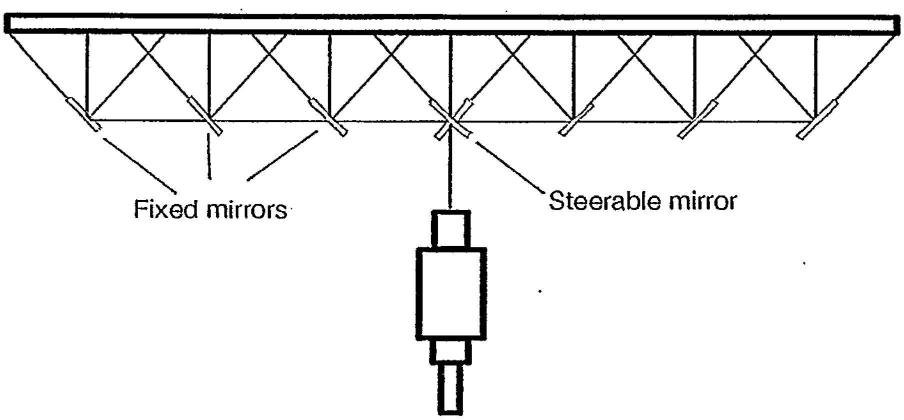


Figure 3.5. Scanning system for the Dantec Laser Doppler Vibrometer.

3.3.4 Estimated Costs of Implementation

Again it was not possible to obtain a great deal of hands-on experience with the 55x Laser doppler Vibrometer system. The authors did visit the Dantec sales office in Allendale, N.J. for a laboratory demonstration of the device. While there, a member of the R&D staff described a proposal to us that they had once prepared for a scanning system with very similar technical requirements to those of this project. Their proposed system would have measured the three dimensional velocity information at various points on a test subject measuring 5x20 feet. Spatial resolution was to be better than 0.01 inches with a measurable frequency range from DC to 50 KHz. It was to be capable of scanning 64,000 points per hour, which corresponds to a random sampling rate of 17.8 Hz. Standoff distance was to be limited to less than 20 feet.

The proposed measurement system used a single high speed, very high precision x-y mirror scanner with a digital controller in a manner similar to scheme (b). No intermediate mirrors were to be used to steer the beams to their measurement locations. This placed great demands on the precision of the mirror table and controller, which were consequently very expensive. Dantec quoted a price of approximately $400,000 to develop such a system one year ago, which was never built.

3.4 B+K Laser Velocity Transducer Type 8323

This unit is manufactured by Bruel and Kjaer in Denmark and marketed here by their Canadian subsidiary, Bruel and Kjaer Canada Ltd..

3.4.1 Principal of Operation

Like the Polytec and Dantec instruments, the B+K unit is based on detecting the doppler frequency shift in backscattered light from a moving surface. The measuring head, processing electronics and laser are all included in a single "black box" in a manner similar to the Dantec unit. There are two measurement modes, velocity and displacement.

3.4.2 Performance With Respect to the Critical Criteria

The velocity nomogram for this unit is similar to that of the two units discussed earlier. The lower frequency limit is quoted as DC when operating in the velocity mode. At a frequency of one Hertz the sensitivity in this mode is given as $20x10^{-6}$m. The unit is limited to frequencies of 0.3 Hz. and peak amplitudes of 7mm or less when operating in amplitude mode. This represents a potentially severe restriction, considering that much larger low-frequency oscillations are expected when modal testing the proposed membrane structure. Maximum standoff distance is only 80 mm. All other aspects of this instrument's performance are expected to be similar to the Dantec unit. Technical specifications are given in appendix D.

3.4.3 Development Required for Implementation

Since this unit also uses a Helium-neon gas laser as it's light source, it too must be protected from vacuum. This would require that either a protective enclosure be built or the unit be located outside the test chamber. Development would be generally similar to that required for the Dantec unit discussed previously.

3.4.4 Estimated Cost

The basic unit costs $18,000. A B+K type 2815 power supply is also required, at an additional (estimated) cost of $5,000. The development costs for a beam steering system are again impossible to project until more is known about the structure and testing method to be used, but would be similar to those of any of the other systems.

3.5 Zimmer MODEL 600 Laser Proximeter

This unit was manufactured by Zimmer OHG of Rossdorf, West Germany and marketed in Canada by Optikon of Waterloo, Ontario.

3.5.1 Principal of Operation

Unlike the Vibrometers discussed in previous sections, the laser proximeter measures absolute displacement between the test object and the measurement head. Although it uses laser light, the principal is not based on interferometry and doppler shifts but rather on determining the location of the bright spot of light it produces in its image field. The laser is a solid state type rather than gas and emits a series of infared (invisible) 80 μs pulses within a 200 μs duty cycle. A schematic of the instrument is shown in Fig. 3.6.

As the surface of the object moves, it diffusely reflects light back to the lenses which focus it as an image of the bright spot onto the photodiode strips. The photodiodes produce an electrical signal which varies in a manner proportional to the position of the spot on the strip, which changes as the test surface moves. Two strips are used, possibly to eliminate the effects of surface rotation. In any case, the device measures the absolute standoff distance and is unaffected by variations in the surface finish.

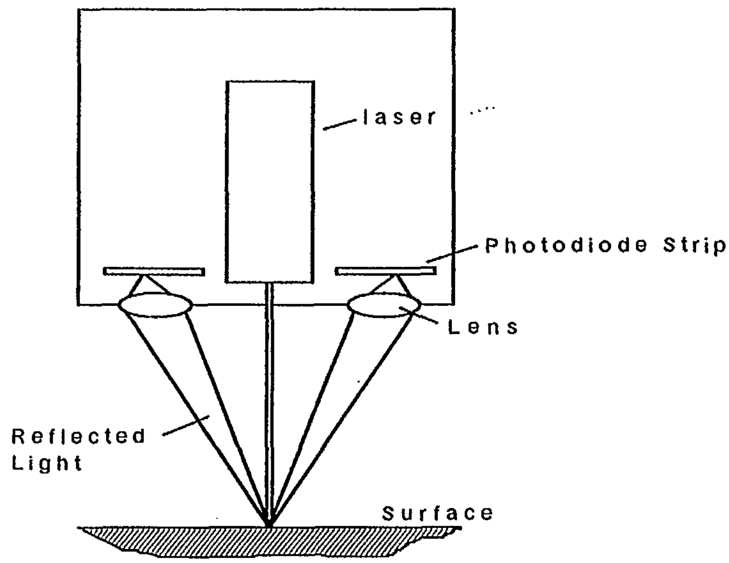


Figure 3.6. The Zimmer Laser Proximeter.

3.5.2 Performance With Respect to Critical Criteria

The unit can be purchased in five versions, depending on the range of motion to be measured. These vary from 0-10 mm to 0-200 mm, with the required standoff distance and resolution increasing and decreasing accordingly. It appears that ranges greater than 200 mm can be provided on a custom order basis. Appendix E lists specifications for the model range. Since relatively large amplitudes are expected to be encountered in this project it would appear that Model 600/200 would be the most suitable choice.

The output from the device is in 12 bit digital form at a data rate of 1000 samples/second. This is more than adequate for any one single point measurement required in this study. The standoff distance of the Model 600/200 is 0.45 m. Because of its seemingly rugged design and relatively small standoff distance, positioning is not expected to be a problem. The proximeter measures absolute distances to surfaces, so special care would have to be exercised if it was to be used as a scanning device with steady-state excitation. The resolution of the unit is quoted as 0.25% of the measurement range, i.e. 0.5 mm for the Model in question. Spatial resolution should be in the order of 1-2 mm, again well within requirements. Testing time would again be a function of the number of measurements required and the number of proximeters available, as each instrument functions in a manner similar to a conventional accelerometer.

3.5.3 Development Required for Implementation

For single point measurements no further development is required. To the best of the distributors knowledge the device should be able to operate in a vacuum, since the laser is a solid-state semiconductor model. From a technical point of view, n fixed proximeters at n measurement locations would provide a straightforward n channel data acquisition system. Any form of excitation could be used with such a system.

For the proximeter to operate as a slow scanning device, a multi-axis translation system would have to be developed. The tracking would have to be relatively precise, because the device measures absolute displacements between the measuring head and surface. Such a device would only be attractive if steady state excitation were used for the modal tests.

3.5.4 Cost of Implementation

Cost of the model 600 laser proximeter is approximately $16,000. This represents a fixed cost per required measurement channel since the device is designed to operate as a unit, i.e the laser, measuring head and processor are all contained in the same "black box".

To estimate the cost of developing a slow scanning device is impossible at this point, for the same reasons as given in other sections. Were such a system to be developed, the distributor has mentioned that some form of "lease to buy" arrangement might be possible during early development stages.

3.6 MTI Fiber Optic Probes

As mentioned in the interim report, there are non-contacting devices commercially available that do not meet all of the requirements of this study but are relatively inexpensive and could still prove useful in some way. One such device is the so-called 'FOTONIC SENSOR' manufactured by MTI Instruments Division of Latham, N.Y..

Like the Laser Proximeter described in section 3.5, the Fotonic Sensor is an absolute displacement measuring device. That is to say, the instrument measures the absolute distance from the end of the probe to the vibrating surface. The probe itself consists of a bifurcated bundle of high quality glass fibers, half of which act as transmitters of incoherent (non-laser) light while the others act as receivers. The receiving fibers deliver backscattered light from the surface to a photodiode detector that senses the intensity of the captured light.

As mentioned already, these units do not meet all of the critical criteria for the proposed measurement system. Their standoff distance is typically very small and the instrument must be re-calibrated with changing surface conditions. The electrical output of the photodiode detector is slightly non-linear if the displacement amplitude becomes larger than the instrument's relatively small measurable range. More complete specifications are given in Appendix F.

Despite these drawbacks, the MTI model 1000 Fotonic Sensor, for instance, is quite inexpensive ($6,000 to $8,000) when compared to the alternatives previously discussed. The instrument is simple to use, measures frequencies down to DC, reads out in either analog or digital and has 7 meter long fiber optic connecting cables available at reasonable cost. This would allow the probes to be located inside the vacuum chamber while the electronics could stay outside. The probes should not be affected by vacuum, and would be an excellent choice for monitoring small amplitude vibrations.

4. Conclusions

The four month feasibility study of noncontacting vibration measurement methods for the modal analysis of large membrane structures has resulted in the following conclusions:

(1) There is no 'off the shelf' commercial technology available which satisfies all of the critical criteria of performance for this project at a reasonable cost.

(2) A shadow or projected grid Moire system would satisfy most, but not all, of the specified performance criteria. Such a system would be useful for qualitative visualization of individual normal modes of vibration, but would be tedious to use for quantitative studies. The major problem would be the time and effort required to reduce the Moire data by hand to a useable form. It is difficult to completely automate this process.

(3) The laser based vibrometers appear to meet most of the critical performance criteria. These devices are designed primarily for measuring relatively low amplitude, high frequency vibrations but can be extended to measure frequencies of less than one Hertz and amplitudes of many centimeters. They are relatively new to the marketplace, so not much can be definitively said concerning their performance until some 'hands-on' testing is conducted. The cost of a multiple vibrometer system would be prohibitive, but it may be possible to use a single instrument with a steerable mirror multiplexing system to rapidly scan the structure during tests.

(4) The Zimmer laser proximity probe is an extremely interesting device that could bear further study if multiplexing one of the laser vibrometers proves impossible.

(5) A final recommendation for a vibration measuring system for this project cannot be made until more is known about the structure and type of test to be conducted. The choice of excitation in particular is important in deciding between the various options. While waiting for these choices to be made, it is recommended that development be pursued on several fronts simultaneously.

5. Recommendations

As a result of the study to date, it is recommended that the project continue and that development proceed by renting or purchasing equipment for further evaluation. To pursue the development of the various systems the following priorized equipment packages should be obtained at the earliest date possible:

(1)	a)	Lease to purchase a Polytec Model OFV-1100 Fiber Optic Vibrometer from Optikon of Canada.	$3,000/mo.
	b)	Purchase an Aerotech Rotary Stage Model ART 50 with controller from Optikon of Canada.	$6,000
	c)	purchase a PC-AT microcomputer to direct the controller	$3,500
(2)	a)	Lease to purchase a Zimmer Model 600/200 Laser Proximeter from Optikon of Canada.	$1,000/mo.
	b)	Purchase a linear positioning stage plus controller from Optikon of Canada.	$6,000
	c)	Purchase a PC-AT microcomputer to direct the controller	$3,500

3) Purchase an image processing system, consisting of:

Image processing card	$2,400
Software or Processing card	$700
PC-AT microcomputer to host card	$3,500
VCR and display monitor	$800
CCD video camera	$2,100

The first two packages are recommended for the development of point measuring systems while the third is for development of the full-field Moire techniques. Obviously if more than one package is obtained only a single computer would be necessary. The total price, including a one month lease of both the Fiber Optic Vibrometer and the Laser proximeter is $29,600. It is felt that one month each would be long enough to explore the true potential of the instruments.

It should be noted that the Laser proximeters are not stocked in Canada, and a delay of up to four months is to be expected between order and delivery of the instrument. Optikon does have a Fiber Optic Vibrometer available for lease in Canada, but it is their only demonstration model and as such would probably be used for that purpose even during the period of the lease.

Appendix A.

Specifications for image processing equipment.

4800 SERIES SOLID-STATE CCD CAMERA

SPECIFICATIONS

ELECTRICAL

Pickup
Single CCD using frame transfer method

Pickup Area
8.8 × 6.6mm (Corresponding to 2/3" tube)

Active Picture Elements
754(H) × 488(V)

Number of Picture Cells
780(H) × 244(V)

Cell Size
11.5um(H) × 27um(V)

Resolution
Horizontal 565 TV lines (RS-170)
Vertical>350 TV lines

Sensitivity
2850°K faceplate illumination in fc. See Chart 1

Contrast Variation
<5% overall

Scanning System
RS-170, 2:1 interlaced

Video Output
1.0 Vp-p 75 ohms unbalanced

Gamma
0.5 or 1.0 jumper selectable

AGC
6 dB variable gain (peak-average adjustable)
Jumper selectable—on/off

Auto Lens
Peak average adjustable.
(Separate auto lens video eliminates AGC/auto lens interaction.)

Signal-to-Noise Ratio
50 dB (gamma 1, gain 0 dB) Unweighted
55 dB (gamma 1, gain 0 dB) Weighted

Auto Black
Maintain set-up level at 7.5 ± 5 IRE units if picture contains at least 10% black

Power Requirements
AC or DC 12V ± 10%, 0.35A
AC 115V ± 10%, 50/60 Hz with optional wall transformer

Power Consumption
4.2W

ENVIRONMENTAL

Ambient Temperature Limits
- 10° to 50°C (14° to 122°F)

Storage
- 30° to 70°C (-22° to 157°F)

Humidity
Up to 95% relative humidity

Vibration
5 to 60 Hz with 0.082 inches total excursion (15 g's@60Hz). From 60 to 1,000 Hz, 5 g's rms random vibration without damage.

Shock
30 g's in any axis under non-operating conditions per MIL-E-5400T, Paragraph 3.2.24.6.

Altitude
Sea level to equivalent of 10,000 feet (20 inches of mercury).

MECHANICAL

Dimensions
See Figure 1

Weight (less lens)
15.5 oz

Lens Mount
"C" Mount, 16mm Format

Lens
See Ordering Information

Camera Mount
1/4-20 threaded holes. See dimensional drawings.

Connectors
BNC Connector—Video out
Switchcraft TB4M—Lens drive
Switchcraft TB3M—Power in
Hirose SR30-10R-6S—Auxiliary

COMPLIES WITH FEDERAL COMMUNICATIONS COMMISSION RULES & REGULATIONS PART 15, SUBPART "J".

SENSITIVITY	With IR Filter	Without IR Filter
Usable with AGC	.02 fc (0.2 Lux)	.007 fc (0.07 Lux)
Full video, Non-AGC	.15 fc (1.5 Lux)	.032 fc (0.32 Lux)
Full video, AGC	.07 fc (0.7 Lux)	.015 fc (0.15 Lux)

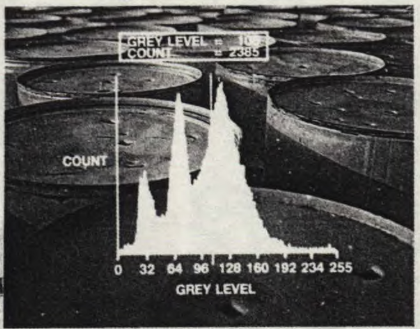
Chart 1

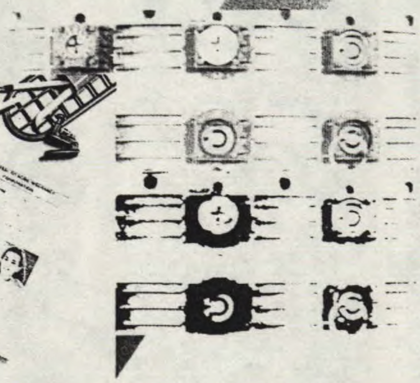
gitizer for IBM* PC XT/AT

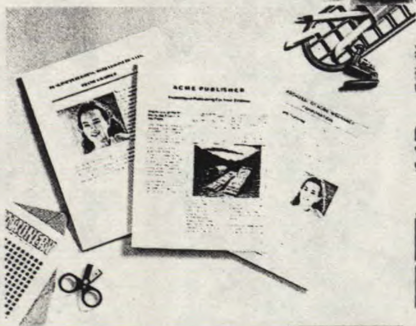
e Computers, Inc.

VFG-512-8G $2,233
VFG-512-8BC $2,513
C-subroutine library $273

ProVision $693







STRAWBERRY TREE GRAY SCALE FRAME GRABBER VFG-512/256

Strawberry Tree's Frame Grabber offers a low cost solution to image acquisition and processing. The VFG-256 and VFG-512 are video digitizers that process, in real time, images from standard cameras, VCR, and other composite video sources. The captured image can be manipulated and displayed on a video monitor.

The Frame Grabber is supplied with software that allows one to perform basic image processing as well as the saving and retrieving of images. A diagnostic program for verifying the hardware is also provided.

SPECIFICATIONS

INPUT:
RS-170, RS-330, CCIR composite video signal

OUTPUT:
RS-170, CCIR compatible signal displayed on video monitor, RGB pseudo color (optional)

SCREEN RESOLUTION:
256 × 256 pixels (VFG-256)
512 × 512 pixels (VFG-512)

NOTE: VFG-256 can be upgraded to VFG-512 for higher resolution.

PIXEL INTENSITY:
64 gray levels (6 bits) or 256 gray levels (8 bits)

FRAME MEMORY:
64K × 8 bits (VFG-256)
256K × 8 bits (VFG-512)

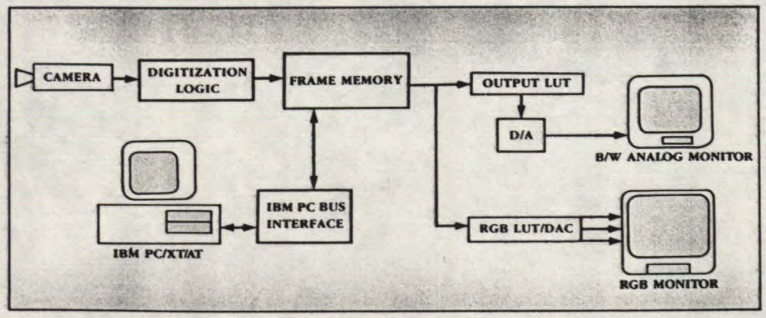
ADDRESS SPACE:
64K bytes

DIGITIZATION RATE:
1/30th second per frame (RS-170) or
1/25th second per frame (CCIR)

OUTPUT TABLE:
Four 256 × 8 bits look-up tables
Three 256 × 6 bits RGB look-up tables (Optional)

APPLICATIONS:

* Robotic Vision
* Factory Inspection
* Medical Imaging
* Security Surveillance
* Office Automation
* Academic Research



Appendix B.

Specifications for the Polytec Fiber Optic Vibrometer.

Polytec

Technical Specifications

Technical Data

	Velocity Demodulator	Amplitude Demodulator
Amplitude sensitivity:	< 1nm	$\lambda/2$ = 316.5 nm for a He-Ne-Laser
Velocity Range:	10^{-4} m/sec – 10 m/sec	0.3 x 10^{-6} m/sec – 10 m/sec
Output:	analog +/– 10 V	analog +/– 10 V digital 12 bit TTL

Ranges of Measurement:	5 mm/(sec·V), 25 mm/(sec·V), 0.25 m/(sec·V), 1 m/(sec·V)
Acceleration Range:	From 0 to over 300 g
Dynamic Range:	> 160 dB over four ranges
Response Time:	170 ns with a step-function change in velocity of 0 m/s to 10 m/s
Dimensions of Signal Processor:	470 mm x 190 mm x 500 mm (WxHxL) 18.5 in. x 7.5 in. x 19.7 in.
Weight of Signal Processor:	approx. 20 kg (44.1 lbs.)
Power Supply Requirements:	110/220 V/+/– 10%, 50/60 Hz, 150 W

Polytec GmbH was founded in 1967 and has since then been engaged in the development and manufacture of electro-optic measurement systems. The fiber-optic Laser Vibrometer is the culmination of work in the areas of Laser Velocimetry, Fourier Spectroscopy and Fiber Optics. The Vibrometer belongs to a family of state-of-the-art optical measurement systems, including measurement interferometers, testing equipment for robots and tooling machinery, laser velocimeters and particle analyzers.

U.S.A.

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OFV-2E-709-1000

Appendix C.

Specifications for the Dantec 55x Laser Doppler Vibrometer.

Technical Data

Amplitude Range of Vibration
10^{-8} m to 1 m
Frequency Range of Vibration (VCO output)
DC to 0.74 MHz
Velocity Range of Vibration
10^{-6} m/sec to 3 m/sec
Acceleration Range of Vibration
10^{-11} m/sec^2 to $0.3 \cdot 10^6$ m/sec^2
Measuring Distance in the Standard Version
1.2 m to 20 m
Response Time: 1 μsec
Slew Rate (Maximum Rate of Change of Frequency)
63 MHz/msec
Equivalent Random Noise with good optical signals
1.2 nV/$\sqrt{Hz}$
Dynamic Range
>160 dB
Noise (Δf = 2 kHz)
- 86 dBm
Analog Output (55N20)
1 V to 10 V/100 Ω/DC to 27 kHz
Spectrum Output (55N20)
Voltage Range: 1 V to 10 V
VCO Output (55N20)
Voltage Range: 1 V to 10 V
Sweep Input (55N20)
Voltage Range: 1 V to 10 V/Low
Digital Output (55N20)
Range
Filter (Local and Remote)
Doppler Frequency: 8 Bits
Frequency Shift
Computer Handshake
Beam Expander
Achromatic Lens, Focal Distance f = 10 mm;
Exchangeable Lens, Focal Distance f = 75 mm and focusing range: 1.2 m to ∞
Mounting Thread:
1", 32 threads per inch (standard C-mount)
Auxiliary thread
58 X 0.75 mm
Retarder Plate
λ/4 (holder with friction)

Measuring Volume
Diameter $d = 4\lambda b/\pi D$
Length $l \cong 8\lambda b^2/D^2$
where b is the distance from the front lens to the measuring volume. D is the diameter of the outgoing beam, D = 9 mm.
(He-Ne laser line, λ = 633 nm)
Power Supply
+18 V/40 mA/50 Ω
The power is supplied from the 55N20 LDA Doppler Frequency Tracker through the 55N10 LDA Frequency Shifter and via the signal cable to the 55L66 Vibrometer Section
Temperature Range: +5°C to +40°C
Humidity: 20 %/80 %
Weight: 8.9 kg (incl. laser)

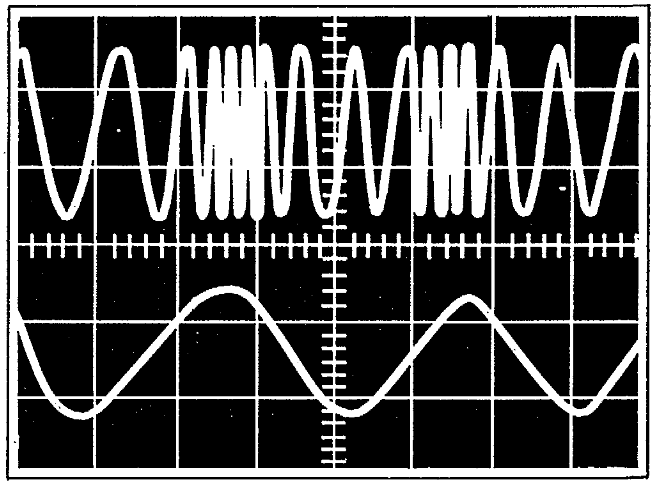

Fig. 5. Upper curve (a): Doppler Signal. An oscilloscope is connected to Monitor Out (55N20) Lower curve (b): vibration signal. An oscilloscope is connected to Analog Out.

Vibration Frequency Range	Max. Doppler Frequency	Max. Slew Rate	Calibration Factor
0.74 kHz	10 kHz	210 kHz/sec	$0.3164 \cdot 10^{-3}$ m/sec/Volt
2.4 kHz	33 khz	630 khz/sec	$1.04 \cdot 10^{-3}$ m/sec/Volt
7.4 kHz	100 kHz	6.3 kHz/msec	$3.164 \cdot 10^{-3}$ m/sec/Volt
24 kHz	333 kHz	63 kHz/msec	$10.4 \cdot 10^{-3}$ m/sec/Volt
74 kHz	1 MHz	630 kHz/msec	$31.64 \cdot 10^{-3}$ m/sec/Volt
240 kHz	3.3 MHz	6.3 MHz/msec	$104 \cdot 10^{-3}$ m/sec/Volt
0.74 MHz	10 MHz	63 MHz/msec	$316.4 \cdot 10^{-3}$ m/sec/Volt

Table 1. The Calibration Factor, for the 55L66/X66 Laser Doppler Vibrometer System (λ=633 nm)

DANTEC

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Appendix D.

Specifications for B+K Laser Velocity Transducer Type 8323.

Specifications Type 3544 (2815 + 8323)

OFFSET VOLTAGE
Velocity: for 1 m/s range, ± 50 mV
for 0,2 m/s range, ± 30 mV
Displacement: ± 20 mV

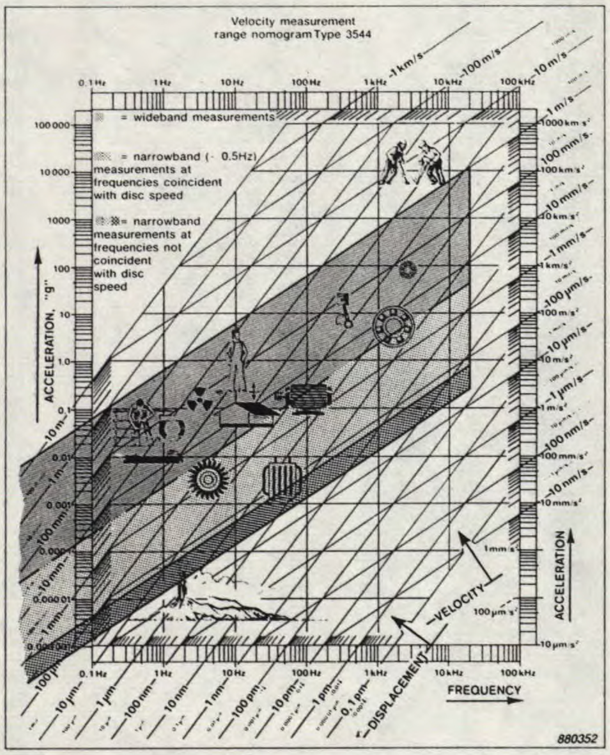
DIMENSIONS (in carrying case):
Height 550 mm
Width 670 mm
Depth 250 mm

WEIGHT: (in carrying case with batteries)
21 kg

RETROREFLECTIVE TAPE DU 0164:
Weight 17 mg/cm^2
Thickness 0,1 mm

ACCESSORIES INCLUDED WITH 3544:
Transducer Power Supply 2815
Laser Velocity Transducer 8323
Carrying case .... KE 0276
Battery pack .... QB 0040
Battery Charger for QB 0040 .... ZG 0166
Angle mirror adaptor .... UA 0965
Tripod .... UA 0989
Connecting cable .... AO 0308
7-pin plug .... JP 0703
One BNC-to-BNC cable, 1,2 m .... AO 0087
5 lots of reflective tape .... UA 0965
Instruction Manual

ACCESSORIES AVAILABLE:
Reflective Tape .... DU 0164
Spare battery pack .... QB 0040
Service Manual



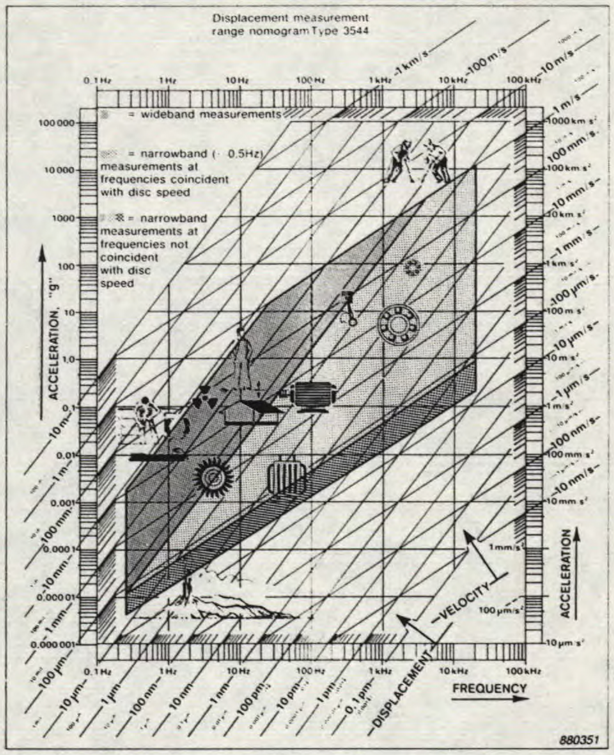


Fig.3. The frequency and dynamic measurement ranges (in velocity mode, left, and displacement mode, right) of the Type 3544, indicating the possibilities when the output of the Type 2815 is fed either into wideband analyzers such as voltmeters and measuring amplifiers, or into narrowband analyzers such as FFTs. Two areas are shown for narrowband analysis, depending on whether the frequencies of interest correspond to harmonics resulting from the two rotating disc frequencies (4 Hz and 15 Hz). The upper limit is the peak level, whereas the lower limits are RMS levels. The ouput limit of 7 V from the integrator in Type 2815 causes the slope of the upper limit between 0,3 Hz and 12 Hz in displacement mode

Range Setting on 8323	Measurement mode on 2815	Equivalent Noise (RMS)	Maximum Velocity (or Displacement) (Peak)	Tolerance
0 – 0,2 m/s	VEL. 0 – 2 kHz	1 mm/s	0,2 m/s	± 0,2 dB
0 – 0,2 m/s	VEL. 0 – 20 kHz	1,5 mm/s	0,2 m/s	± 0,5 dB
0 – 1 m/s	VEL. 0 – 2 kHz	1,5 mm/s	1 m/s	± 0,5 dB
0 – 1 m/s	VEL. 0 – 20 kHz	2,5 mm/s	1 m/s	± 0,5 dB
0 – 0,2 m/s	DISP. 0,3 – 20 kHz	20 μm	7 mm	
0 – 1 m/s	DISP. 0,3 – 20 kHz	20 μm	7 mm	

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Table. 1. Wideband measurement limits for the Type 3544 with different range settings on the Type 8323 and different bandwidth and vibration parameter settings on the Type 2815

Brüel & Kjær

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Japan 03-435-4813 · Republic of Korea 02-793-6886 · Norway 02-78 70 96 · Singapore 225 8533 · Spain (91) 268 10 00 · Sweden [illegible] · Switzerland [illegible]
Taiwan (02) 713 9303 · USA (617) 481-7000 · Local representatives and service organisations world-wide

Appendix E.

Specifications for Zimmer Model 600 Laser Proximeter.

Specifications: Laser Proximeter Model 600

(Model)		600/10	600/20	600/50	600/100	600/200
Range S	(mm)	0–10	0–20	0–50	0–100	0–200
Standoff A	(mm)	90	130	130	270	450
Resolution	(μm)	2.5	5	12.5	25	50
Error	($\pm\mu$m)	10	20	50	100	200
Spot diameter D	(mm)	0.7	1.5	3.5	7	14
Aperture width B	(mm)	80	110	110	160	160

Range: 0–10 mm to 0–200 mm (see table) other ranges upon request

Resolution: 0.25% 1)

Noise: 0.025% 1)

Error: ± 0.1% 1) 2)

Measurement signal: 12 bit binary parallel positive 3) (0–4000 ≙ 0–100% of range)

Data rate: 1000/s

Band width: 0–2 kHz (–3 dB)

Reflectivity of target: 5 to ~ 100% without influencing the precision

Control signals:
1) Alarm Signal: High if no diffuse reflecting surface in the field of view, Laser defective or loss of power 3)
2) Inhibit Out: Low if data transfer is stopped (pulse width: 50 μs) 3)
3) Inhibit In: stores last measurement when shorted to ground (1 mA, 5V)

Laser: solid state Al Ga As

Laser output: 20 mW

Peak emission: 800–900 nm

Pulse duration: 80 μs

Duty cycle: 200 μs

Pilot light: green: normal operations; red blinking: insufficient diffuse reflectivity or Laser defective

Max. ambient light: 1000 Lux

Shock vibration: < 5 g in all axes

Operating temperature: 10–40°C

Temperature error: ± 0.025%/K

Max. Rel. Humidity: 90%

Power: 100, 117, 220, 240 V ± 10%, 50–60 Hz, 30 VA

Enclosure: Aluminium, anodized, safety class IP 55

Weight: Approx. 4 kg

1) of range

2) Larger errors can be expected if target surface does not have ideal diffuse reflectivity. Such errors can be accounted for if instrument is factory calibrated individually.

3) open collector 30 V, 80 mA

Appendix F.

Specifications for MTI Fiber Optic Probes.

SPECIFICATIONS

Probe Plug-in Modules

Plug-in Model Number	Probe Number	Probe Tip Diameter (in.) Total	Probe Tip Diameter (in.) Active	Probe Length (in.)	Frequency Response (-3 db) (kHz)	Output[1] Signal Ripple (mV p-p)	Resolution[2] (% of Range) Dynamic[3]	Resolution[2] (% of Range) Static[4]	Front Slope Sensitivity[5] (μin./mV)	Front Slope ± 5% Linear[6] Range (mils)	Front Slope Standoff[7] (mils)	Back Slope Sensitivity[5] (μin./mV)	Back Slope ± 5% Linear[6] Range (mils)	Back Slope Standoff[7] (mils)	Optical Peak[8] (mils) Midpoint[9]	Optical Peak[8] (mils) Range[9,10] ± 5%
MTI-3802	020R	.020	.007	36	10	50	.4	.1	.5	3	2	2.5	15	15	10	3
MTI-3804	032R	.032	.019	36	30	40	.3	.07	.55	3	2	5	25	25	12	6
MTI-3806	047R	.047	.027	36	40	35	.3	.05	.6	3.5	2.5	8	30	30	14	11
MTI-3808	062R	.063	.047	36	60	30	.2	.05	.6	3.5	2.5	10	35	35	16	12
MTI-3810	062H	.063	.047	36	60	30	.4	.1	3.0	14	10	12	55	90	50	30
MTI-3812	125R	.125	.086	36	70	20	.2	.05	.6	4	2.5	18	70	55	18	20
MTI-3814	125H	.125	.086	36	70	20	.3	.1	7.0	30	25	30	150	200	120	60
MTI-3816	125CTI	.125	.086	36	70	20	.3	.1	3.5	15	12	25	80	140	75	50

NOTES:

[1] On unexpanded range, increases with range expansion but overall signal-to-noise ratio improves (see resolution).

[2] Utilizing full range expansion, % of front and back slope range, when measuring to a 2 μin. AA electroformed GAR surface finish comparator block.

[3] Using vibration display oscilloscope or external recorders; 5x improvement on 3800 series when filter is used.

[4] Direct reading on panel meter, 5x improvement using digital readout option (KD-DRO).

[5] Nominal value, may vary ±10%.

[6] For approximate ±1% linear range, multiply by 0.75.

[7] Nominal value, may vary ±5%.

[8] Optimum standoff for reflectivity/surface finish measurements.

[9] Nominal value, may vary ±15%.

[10] Displacement range producing 5% change from peak output when making reflectivity/surface finish measurements.

OPERATING THEORY

The MTI 1000 Fotonic Sensor transmits light through a fiber optic probe to a target surface. Light reflected from the target surface back through the probe is converted into an electrical signal proportional to the amount of gap of displacement between the probe face and the target surface.

The instrument creates a response curve which graphically compares the amount of reflected light and the amount of displacement between the probe and the target surface. The initial linear rise in the response curve is called the "Front Slope." It is extremely sensitive and it is used for measurements in the microinch range.

The apex of the response curve is called the "Optical Peak" and it provides the output signal sensitivity to light intensity variations required for inspection and comparison of surface conditions. The Optical Peak is also used to calibrate each probe module to establish standard sensitivity independent of target reflectance.

The portion of the response curve decending from the Optical Peak is called the "Back Slope." It is used for measurements which require greater standoff distances and less critical sensitivity and resolution.