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NON-CONTACTING ELECTRO-OPTICAL CONTOURING OF HELICOPTER ROTOR BLADES

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24 April 1980

Final Technical Report

Prepared For:

U. S. Army Aviation Research & Development Command
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Non-contact contour measurements of helicopter rotor blades to accuracies of 0.001" are possible via rangefinding by triangulation employing electro-optical techniques. A prototype of a portion of such a system has been built and tested. The results of these tests indicate that the construction of the full prototype system is feasible and desirable.

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JOB

This project has been accomplished as part of the U.S. Army Materials Testing Technology Program, which has for its objective the timely establishment of testing techniques, procedures or prototype equipment (in mechanical, chemical, or nondestructive testing) to insure efficient inspection methods for materiel/material procured or maintained by DARCOM.

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1. SUMMARY

Dreyfus-Pellman Corporation (D-P) was awarded Contract DAAK-50-78-C-0024 to accomplish the second phase of a three-phase program. This three-phase program will result in a prototype, computer-controlled, non-contacting electro-optical system to measure the contour of helicopter rotor blades.

This report covers Phase II only. The effort called for by Phase I proved the feasibility of the concept and is documented in Dreyfus-Pellman's Final Technical Report dated 11 December 1978 (AMS Code: 5397 OM 6350, M766350).

During Phase II, a full-scale prototype electro-optical rangefinder was designed, built and tested. This system operates under computer control, and can determine the contour of chordal sections of sample helicopter rotor blades to accuracies approaching 0.001". A computer printout shows the X-Y coordinates of as many points on the chordal section as desired. A graphic display can show the chordal section being contoured and the blade section's specification simultaneously. In addition, the differences between these two sets of coordinates are computed and displayed graphically and via printout.

The final system (Phase III) will permit the contouring of an entire helicopter rotor blade in 30 minutes by electro-optical techniques without contact between contouring equipment and the surface being measured. The contouring system elements will be several feet from the surface being contoured.

The entire operation is under computer control and fully automatic. It can be changed by reprogramming to contour a wide variety of surface shapes. Expensive tooling need not be fabricated for each part being contoured. Operator skill needed is minimal, as all functions are under computer control.

Output format can be varied to suit the individual user.

To test contouring accuracy, mechanical measurements were made, using a Brown & Sharpe Validator, to determine the coordinates of approximately 30 points, including the leading edge on each of three different chordal sections of helicopter rotor blades. The electro-optical rangefinder contoured these three rotor blades along the same chordal line, and the mechanical coordinates were fitted to the electro-optical contour. The root-mean square (RMS) of the difference between the mechanical coordinates and the electro-optical contour varied between 0.0016 and 0.0026".

To determine scale, a chordal section of a rotor blade was contoured; it was then moved approximately one inch along its chord and recontoured in its new position. The difference between these two contours was 0.0028" RMS.

In order to determine how well the electro-optical equipment can measure the leading edge of a swept-back rotor blade, a section of an AAH blade was tilted approximately 20° and contoured by the electro-optical rangefinder. This contour was compared to points measured by the Brown & Sharpe Validator. The difference between the mechanical points and the electro-optical contour was 0.0021" RMS.

In order to determine absolute accuracy, a special test fixture was built and measured with traceability to the National Bureau of Standards. The results of these tests indicate that absolute accuracy in the order of 0.001" to 0.002" is attainable.

1. BACKGROUND

The aerodynamic characteristics of main rotor blades of helicopters has always been considered a critical parameter by the industry. One of the major manufacturing problems has been to accurately determine the as-built configuration. There have been three basic measuring methods used typically; mechanical, electro-mechanical and pneumatic mechanical. In most cases, these methods are constrained in application to predetermined chordal stations, and the measuring devices are moved from point to point along the span of the blade. The number of data points has been limited and the amount of time required to take the measurements is relatively long. There is significant concern in the industry regarding the correlation of as-built configuration and performance. There are schools of thought that feel by knowing more about the surface condition of the blade and by having better data to relate to theoretical airfoil, it may be possible to relax manufacturing tolerances without sacrificing performance. The result would be the availability of a comparatively less expensive blade.

These types of measurement equipment are subject to frequent failure. The two predominant modes are total malfunction and inaccurate data. As a result of these frequent problems, the equipment requires reasonably high investment and maintenance costs. In many cases, the data derived from these measurement devices are not easily coupled to any form of computer. It has long been the desire of the industry to have fast, accurate measuring equipment easily adjustable to any number of data points along the chordal dimension in conjunction with the data processing capability that provides a summary assessment of the surface of the blade. An additional characteristic that is needed is a measurement device with the versatility of accommodating various sizes of blades and airfoil shapes without the necessity of complete and extensive retooling. The D-P electro-optical system offers a promising solution to these problems. It is capable of measuring any form of airfoil; it can be programmed to provide almost an infinite number of measurements along the chord and the span of the blade. The resulting signals from the measuring devices are easily converted to a form usable in a basic computer, thereby allowing comprehensive assessment of the as-built configuration covering all parameters such as camber, twist, waviness, chordwise bow, and spanwise bow. In addition, contour measurements will be made in the area of and at the leading edge.

2. ADVANTAGES DERIVED FROM THIS TECHNIQUE OF CONTOUR MEASUREMENT

The Noncontacting Electro-Optical System to automatically measure the contour of helicopter blades designed by Dreyfus-Pellman Corporation is based upon solid,highly-reliable, proven electro-optical components and engineering practice. A breadboard of the Electro-Optical Rangefinder, which is the heart of the proposed system, was built, tested and demonstrated under Contract DAAK 50-78-C-0008(P6D) with the Army Aviation Systems Research and Development Command. A Prototype, Computer-controlled Electro-Optical Rangefinder was built, tested and demonstrated under contract DAAK 50-78-C-0024, with the Army Aviation System Research and Development Command. The tests performed under this contract show that helicopter rotor blades can be measured, using this concept,to accuracies of 0.001" in a reasonable and practical way. A complete system which can be used to contour helicopter rotor blades is proposed for Phase III of the overall program.

The combination of the electro-optical subsystem with modern electronic data processing components results in a powerful, flexible, system that can be used in a factory and/or engineering environment to perform measurements on helicopter rotor blades to an accuracy and with speed which represents an advance in the state of the art.

If one were to build conventional equipment, employing contact probes or proximity probes to make the required contour measurements, the accuracy of these measurements would depend upon the stability of the mechanical structure which serves as a reference. Any twisting, bending or settling of the structure after calibration or during measurement would affect the accuracy of the machine. Probes must cover over 40 feet spanwise and 48 inches chordwise, with a positional accuracy of better than ±.001 inch under normal shop conditions. The cost and complexity of a mechanical X-Y carriage positioning a probe with this accuracy is extremely high. If multiprobes are used, the relative position of one to the other must be known and held to better than ±.001"; this is expensive also.

In addition, conventional equipment affords little or no flexibility in operation. Once the probes are positioned for a certain type of blade, rearrangement, which can be costly, is required before any other size blade can be measured. The proposed system need not be rearranged. All that is required is operator control or reprogramming for automatic measurement.

The use of the proposed machine to measure rotor blade contour will enable helicopter manufacturers to:

1. Improve vehicle performance.

2. Reduce vibration so that the helicopter would be a better platform for the payload. This would enhance payload performance and extend payload operating life.

3. Reduce vibration so that rotor and gear box life would be extended.

As to factory environment, our design offers the following advantages over conventional mechanical or electro-mechanical contacting systems:

1. Lower operating cost, because setup is simple. Physical changes and calibration are not required for each blade type measurement. Changes are made, via programming, quickly and economically.

2. The mechanical structure is less costly than conventional structures, because the requirements for dimensional stability are reduced by an order of magnitude, due to the self-calibration features of our design and the fact that the balanced rotary motions of the scanner will cause less deflection than the linear motion of conventional contacting probes.

3. Probe wear, together with the cost of probe replacement, is eliminated, as our system is noncontact.

4. Quick and automatic calibration. Reference points can be scanned between each blade measurement in order to calibrate and establish a reference coordinate system from which each blade measure-

ment can be taken. In addition, reference calibration is achieved between each chordwise scan.

5. High thru-put. Measurements are fast. Thirty minutes for an entire rotor blade.

6. Compatible with modern data-processing systems. Outputs can be tailored to meet the desired output format. Summary data and analysis can be made quickly and eonomically.

7. Measurements can be made in the area of and at the leading edge.

The Dreyfus-Pellman system utilizes proven technology; the application of this technology was successfully demonstrated during the first phase of this program and reduced to practice during the second phase of the program. During a proposed third phase, a complete system can be built.

3. AERODYNAMIC AND MANUFACTURING CONSIDERATIONS

Dreyfus-Pellman's coordinate measuring machine, as proposed during Phase III, will provide a blade contour measuring system, which will be accurate and rapid, providing blade measurement data to the operator in a matter of seconds by the use of a minicomputer and a high-speed printer. The data will provide a binary indication of acceptability. When the blade is unacceptable, it will specify the exact parameter and, where applicable, the chord and spanwise location.

For example, the computer will provide for typical blade contour readings at spanwise locations of 20%, 40%, 60%, 75%, 90%, and 95% of blade span. At each spanwise station, readings will be taken at the leading edge and of the chord height at as many points as desired (measurements can be made as close to each other as 0.010"). The readings will be taken simultaneously of the top and bottom of the blade, providing orders of magnitude more data compared to what is presently available.

The computer will calculate top and bottom chordal heights and a printout will provide chordal actual heights and any deviations from requirements. The system will simultaneously show these results graphically on a TV screen. The system is designed so that easy alteration of the standard measurement points can be achieved. This provides the capability of using the system as an analytical tool for evaluating specific aspects of the blade manufacturing tooling reproducibility. It may also be used to evaluate local areas of the blade with regard to comparisons of as-built configurations to aerodynamic performance.

Utilizing the actual dimensions, airfoil waviness and camber of the airfoil at each spanwise station will be calculated and summarized. Additionally, during the course of scanning the blade contour, at the various spanwise stations, the twist of the blade will be calculated and printed out as a part of the data.

Using the aforementioned summary numbers and the blade twist, the computer will calculate and print out the trim tab angular adjustment that will be required to cause the blade to track when installed on an aircraft.

The equipment will provide a structure to facilitate insertion and removal of the blade. It will be front-loaded in a manner that will minimize the need for clearance area around the system.

4. SPECIFIC ACCOMPLISHMENTS

Dreyfus-Pellman was awarded Contract DAAK 50-78-C-0008 (P6D) in October, 1977; this covered the first phase of a multi-phase program to design, build, test, and install a machine to automatically measure the contour of helicopter rotor blades, using non-contacting electro-optical techniques.

The work performed under that contract indicated that the engineering design concept employed by Dreyfus-Pellman Corporation was sound and would result in a machine meeting the performance goals stated in Section 5 of this report.

In September 1978, Dreyfus-Pellman was awarded contract DAAK50-78-C-0024, which covered the second phase of this three-phase program. Under this second phase, the following was accomplished:

1. A prototype computer-controlled electro-optical rangefinder was designed, fabricated and tested, using actual helicopter rotor blade sections constructed of various materials.
2. A graphic display, which showed the actual contour of the rotor blade section being scanned, together with the coordinates of points on its surface which previously were determined mechanically, was designed and built.
3. Programming was completed to the extent that a complete scan of a chordal section could be taken, displayed and printed from a single keyboard command.

Figure 1, 2 and 3 are photographs of the prototype system.

From an economic and practical engineering standpoint, it follows that the work begun in Phase 1 and continued in Phase 2 should continue, and will result in usable factory hardware.

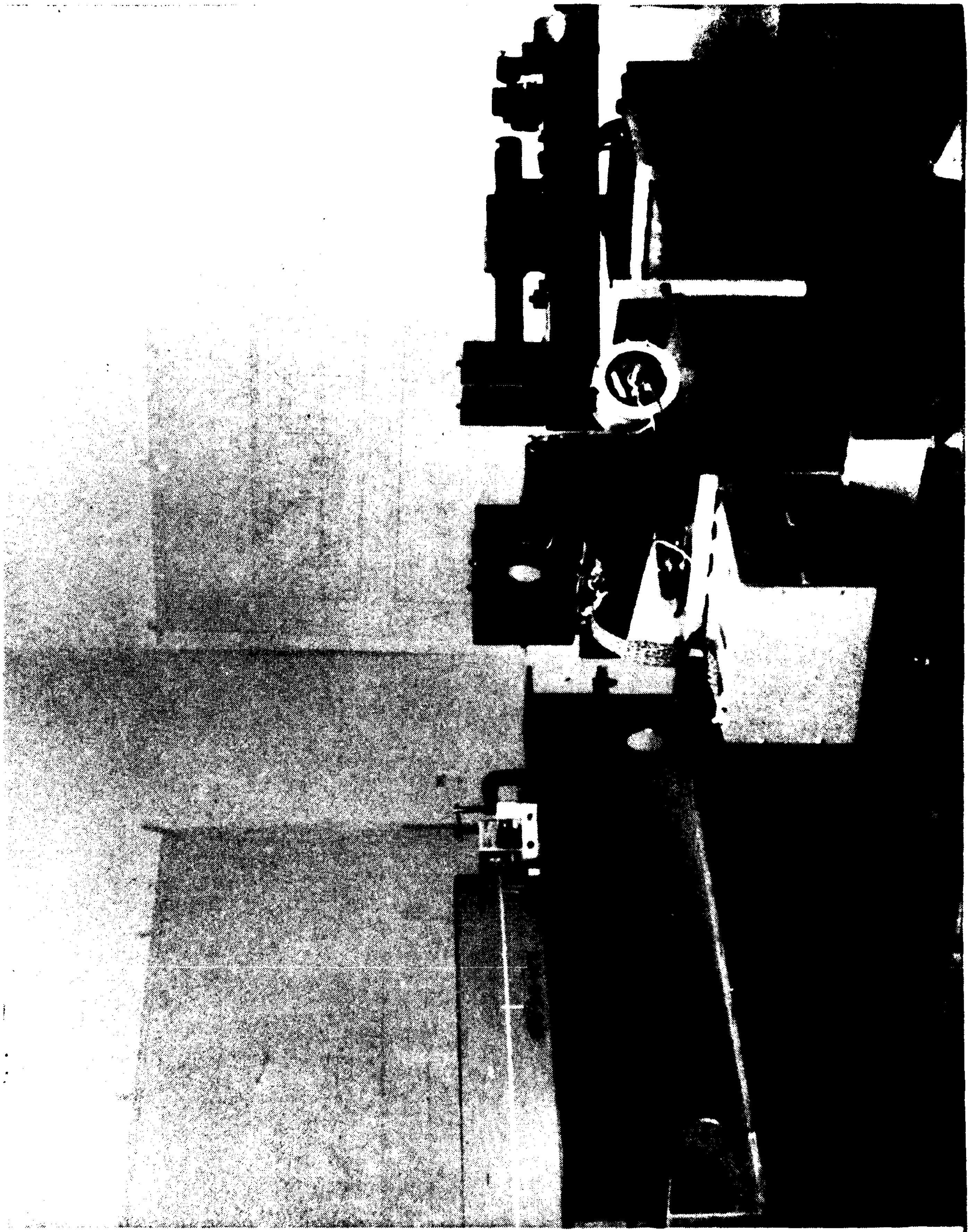


FIGURE 1

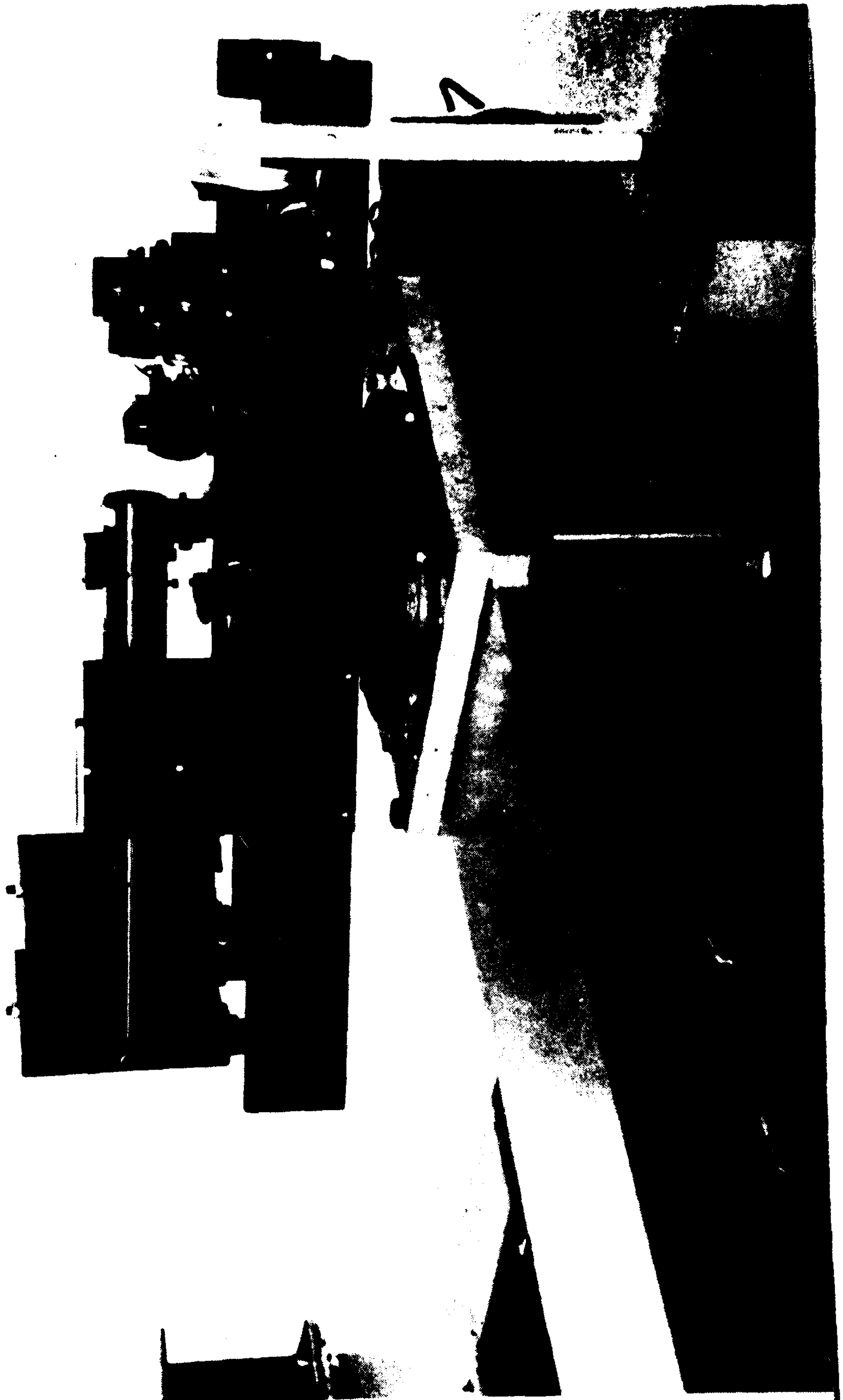


FIGURE 2

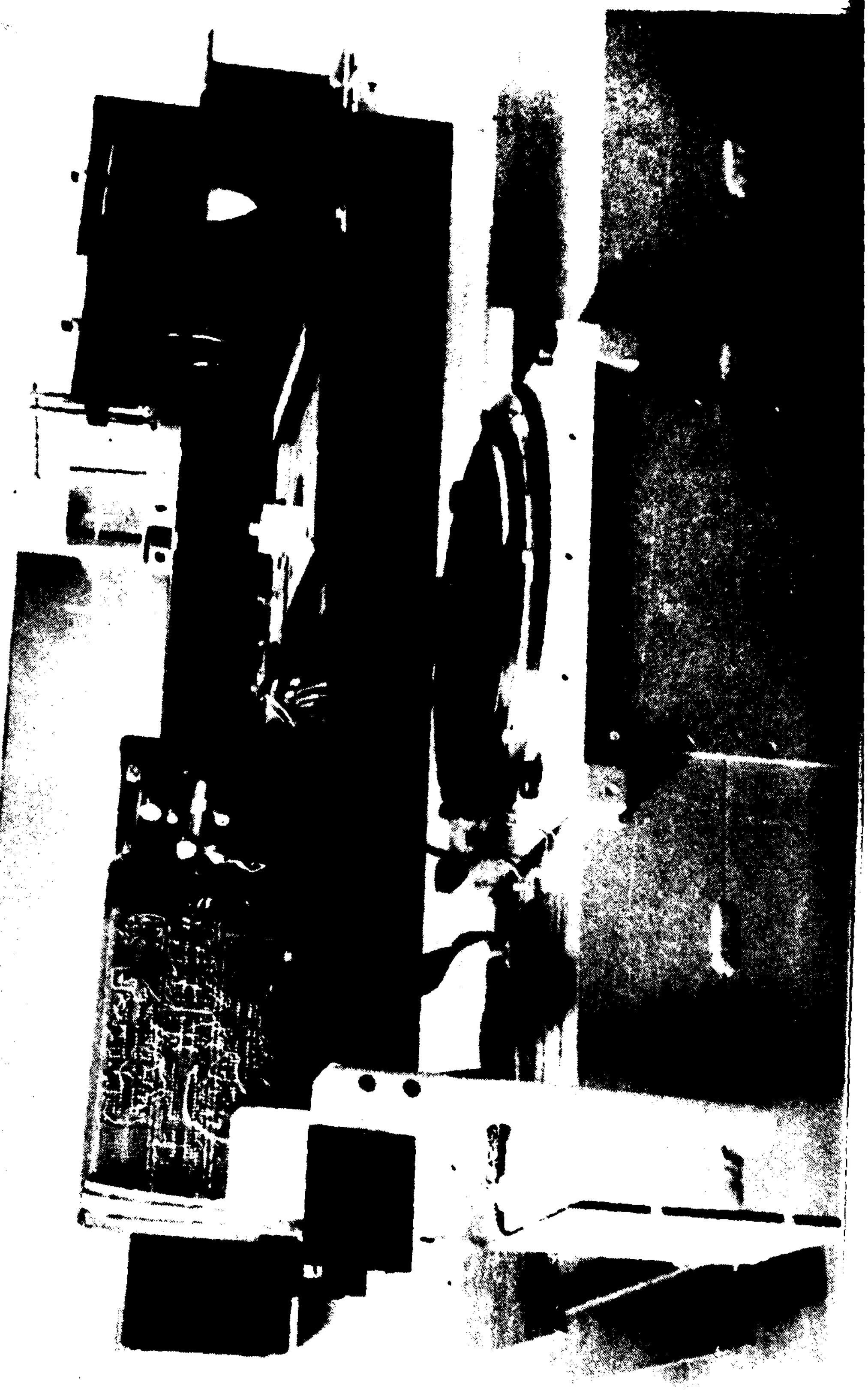


FIGURE 3

5. PERFORMANCE GOALS

The prototype rotor blade measuring machine which Dreyfus-Pellman Corporation proposes to build under Phase III shall be designed to meet performance goals which are based upon manufacturing and engineering requirements which will be encountered over the next ten years.

The proposed machine will work in conjunction with electronic data processing equipment and graphic displays, which will afford a high degree of flexibility. Changes in measuring requirements will be accomplished largely through the use of programming. Mechanical changes to the machine will be held to a minimum. In most cases, the only mechanical change required will be modification or adjustments to the holding fixture to accommodate different size rotor blades. The machine will be designed to provide a high degree of accuracy without any loss of reliability. As a goal, the machine will make the following measurements to the accuracies specified:

1. The primary function and most important objective of this equipment is to measure cross-sectional shape of blades and blade spars. The absolute accuracy of the blade contour relative to a reference plane shall be 0.001". Based upon the contour map of the blade obtained by scanning the cross-section of the blade, including the leading edge at various stations, waviness, camber, flatwise bow, edgewise bow and twist are to be computed. Accuracy for twist shall be one minute of arc and accuracy for flatwise and chordwise bow shall be 0.010".

2. The machine shall have the capability of making measurements as close as 0.010" apart on certain portions of a chordwise scan (for example, at the leading edge). The time constant of the measuring system shall be short enough to permit many measurements to be made in critical areas without slowing down the overall measuring cycle. The number of measurements shall be controlled from a keyboard.

3. The dynamic range of the measuring system shall be great enough to accommodate different blades where the measurement surfaces will vary in location (one from the other) by as much as 5 inches.

4. Spanwise movement along the blade shall be accomplished by automatically moving the carriage of the measuring system. The blade shall remain stationary. Spanwise location of the measuring device shall be automatic, based upon preprogrammed inputs to the machine.

5. A keyboard shall permit the operator to select spanwise position in the event that preprogrammed positions are not desired or if additional positions are desired. When operating in the preprogrammed mode, the machine will automatically move to the next spanwise position at the completion of measurement of the chordwise contours. Spanwise location shall be accurate to 0.030" of true position.

6. A self-calibration feature shall be incorporated into the machine. Calibration shall be checked at the beginning and end of each chordwise scan. The computer system will adjust all readings to account for the calibration inputs.

7. The machine shall accommodate rotor blades having a chord width as large as 48", a span as long as 40', and thickness changes per side as great as 3".

8. The measuring speed of the system shall be such that at least 4000 points may be measured on a 40' rotor in 30 minutes.

9. A graphic display will be provided which will show as desired the contour of each chordal section and will be capable of comparing actual section to specification requirements.

6. SYSTEM DESIGN

Introduction

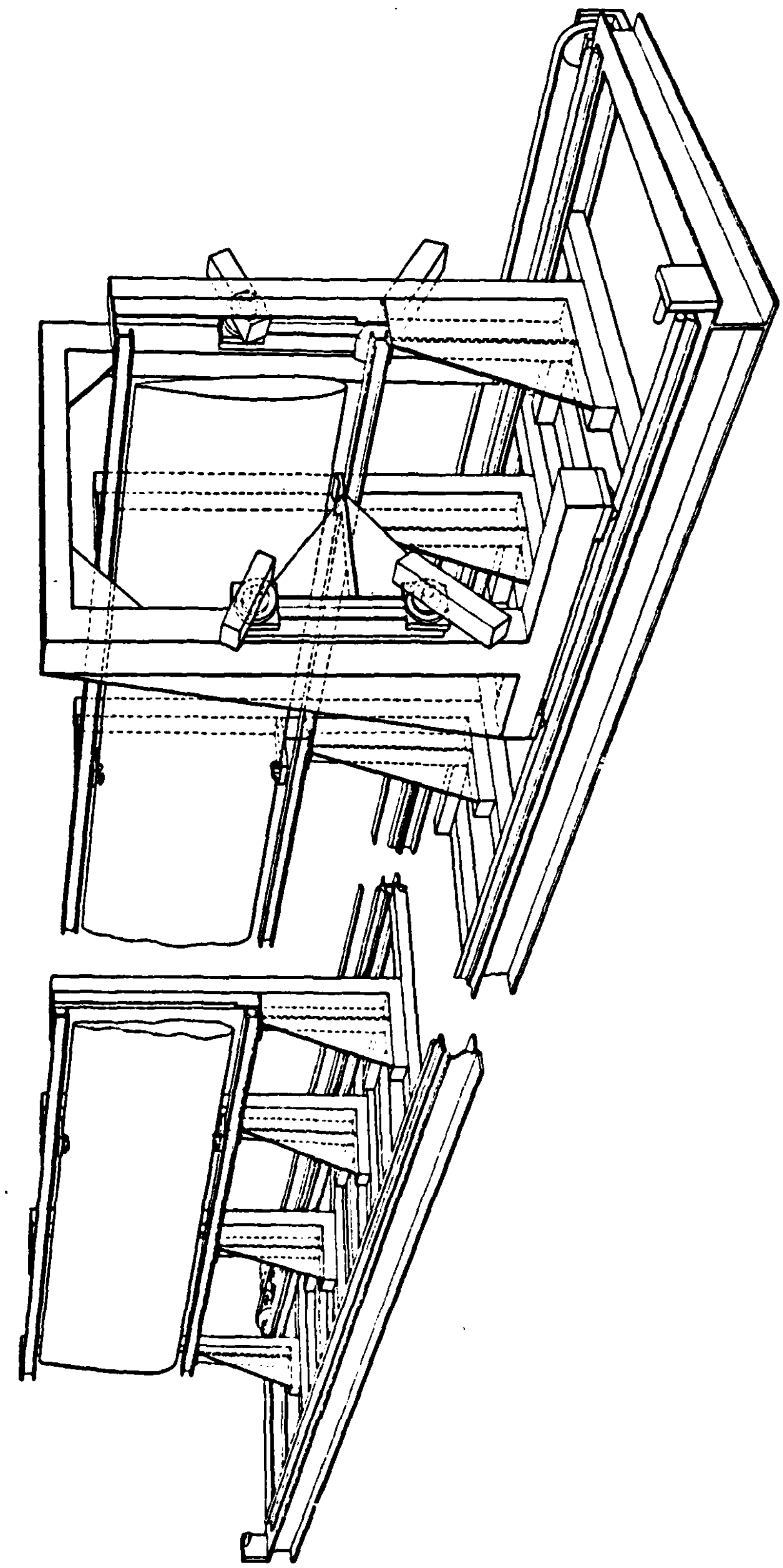
Dreyfus-Pellman Corporation's design utilizes noncontacting electro-optical sensors in a triangulation rangefinder arrangement to measure the contour of helicopter rotor blades. Two such rangefinders are used, so that both sides of the rotor blades can be measured simultaneously. The two sides of the blade are related, in a measurement sense, by having common reference points adjacent to the leading and trailing edge measured by both rangefinders. The use of a small mirror near the leading edge affords a proper viewing angle for this portion of the blade.

Figure 4 shows the contemplated design of the overall system (proposed for Phase III). It is an artist's conception, based upon the preliminary design of the structure completed during Phase I.

The mechanical structure of the complete measuring system consists of two main sections.

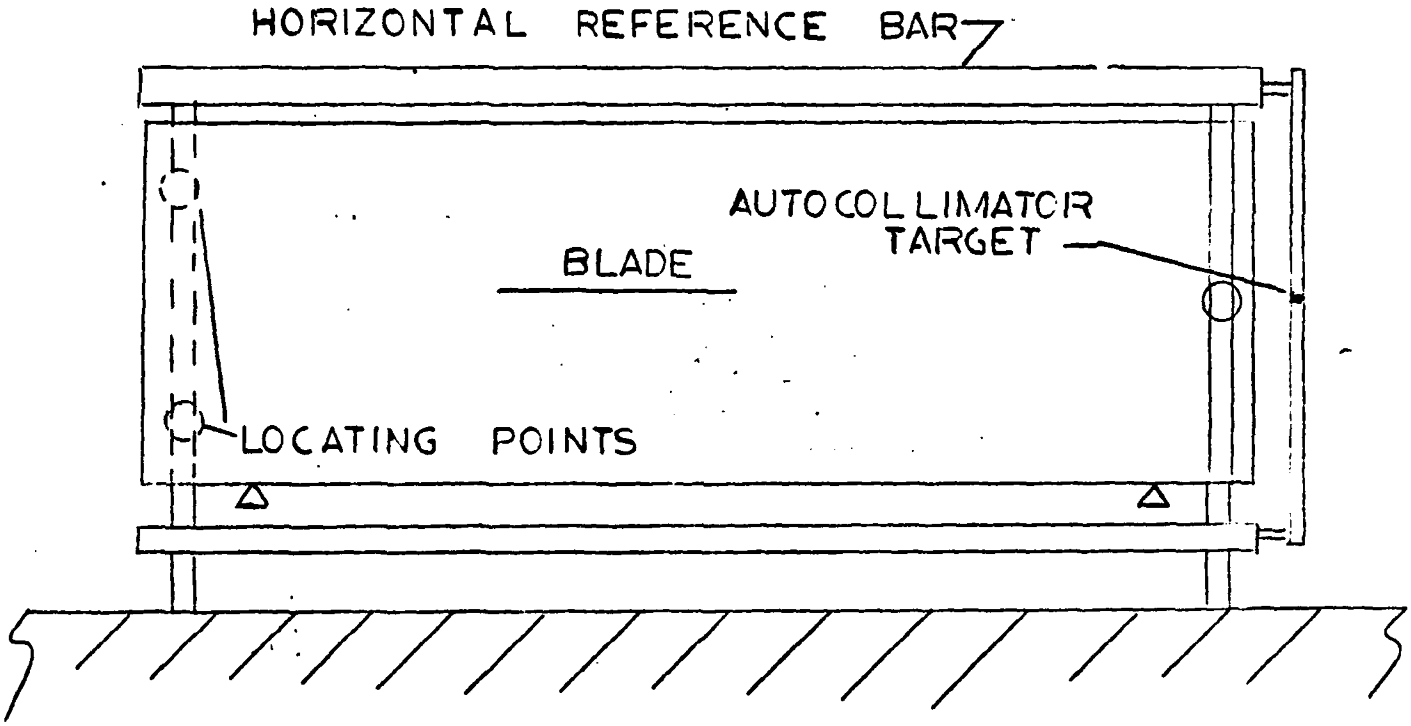
The first section is a fixture which supports the blade being measured. This fixture locates the blade on two reference chords which establish the coordinate system for contour measurement. In addition, optical references are incorporated into this fixture, so that the optical sensor will always look at these references when measuring surface contour (Figure 5). That means that the position of the optical sensor need not be controlled to plus or minus .001" relative to the rotor blade, but that its position be known to plus or minus .001" as determined by scanning the reference bars. This reduces its structural complexity by an order of magnitude.

The second section of the structure is a transporting mechanism which moves the optical sensor spanwise over the blade being measured. The chordwise scanning motion is generated by rotating the Illuminator and Tracker through sufficient angles to scan the entire chord. In view of



SURFACE CONTOURING SYSTEM

FIGURE 4



HOLDING FIXTURE

FIGURE 5

the fact that the exact position of the optical Rangefinder is determined by a physical reference tied to the holding fixture, its position need not be controlled to a high precision. However, its position must be known accurately. This noncriticality of position reduces the cost and complexity of the transporting mechanism. In addition, by isolating the holding and reference fixture from its moving transporting system, its complexity and cost are reduced (Figure 6). The salient feature of this system is that most of the problems associated with mechanical or electromechanical contactors and precision X-Y carriages are avoided. Optical references are established and maintained independent of the structure which carries the sensing and measuring equipment; thus, measurement accuracy does not depend upon the rigidity and stability of the mechanical structure, thereby reducing the cost and complexity of this structure and overall system.

Scanning is accomplished by having a laser Illuminator generate a 0.001" x 0.100" line image on the surface of the rotor blade. This Illuminator is rotated and counterbalanced about its rotation axis. As the Illuminator rotates, the line image travels along the chord of the blade. An optical Tracker captures the line image in its field of view and tracks it as it moves across its chord. The Tracker motion is one of counterbalanced rotation. The counterbalanced rotational motion of the Illuminator and Tracker minimizes shifting of masses on the main supporting frame of the measuring equipment, thus improving measurement accuracy and reducing the cost and complexity of the supporting frame.

The surface contour is measured by optical triangulation rangefinding. The baseline of the triangulation Rangefinder is an approximately 40" long beam supporting a laser light source at one end and an optical tracker at the other end. The baseline beam is suspended approximately 30" above the chord. The laser source generates a beam of light forming one leg of the Rangefinder triangle; the other leg of the rangefinding triangle is generated by the axis of the optical Tracker. The location of the contour point at the apex of the triangle is then defined by angle, side, angle (illuminator angle, baseline, and tracker angle), and can be trigonometrically calculated.

In order to contour the surfaces, the Illuminator pivots so that the laser spot travels across the chord at an angular rate of 3°/second. As the Illuminator beam pivots, the Tracker pivots to track the laser spot under closed-loop servo control, so that the intersection of the illumination axis and tracker axis maps the surface contour. This is accomplished to an accuracy of 0.050". An open loop sensor located in the Tracker determines the position of the laser spot to an accuracy of .0005" (Figure 7).

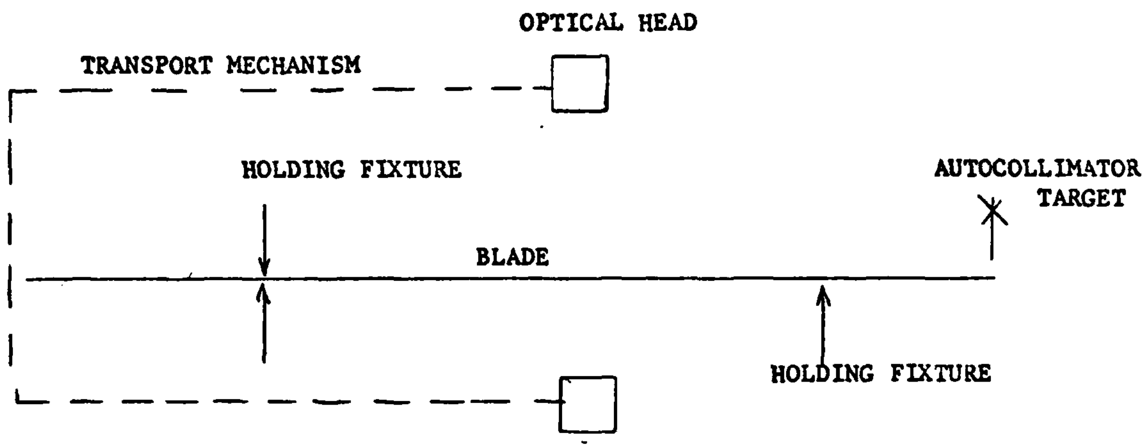
The laser beam is modulated at a frequency of 1 kilohertz, and the optical Tracker is filtered in the spectral (wavelength), temporal (frequency), and spatial (field of view) domains to prevent ambient stray light from biasing the contour readings.

As the laser Illuminator pivots, its beam is kept focused on the surface of the rotor blade by a closed-loop, focusing adjustment on its output lens. The Tracker is likewise focused.

The Rangefinder assembly travels intermittently along the surface's long dimension from measuring station to measuring station. As it travels, the 50' long span girder will tend to settle and twist. Therefore, at the beginning and end of each pivoting scan of the contour, the Rangefinder is calibrated by locating two reference points located near the leading and trailing edges of the surfaces on the holding fixture. The angular orientation of the pivot axis is monitored by an autocollimator connected rigidly to the pivot axis which is looking at a fixed target on the holding fixture.

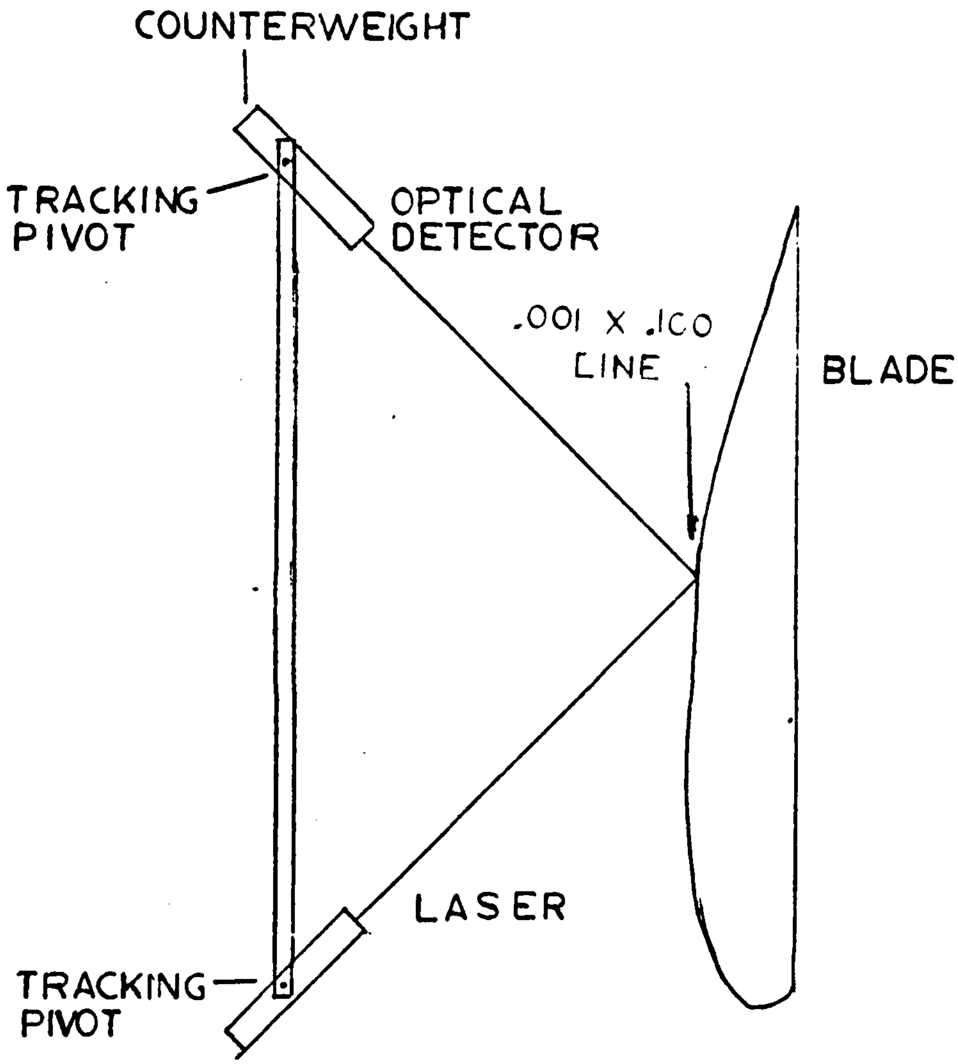
Rangefinder

The Rangefinder consists of two optical assemblies: a laser Illuminator and a contour Tracker, which are located at the ends of a 40' long baseline beam. The baseline beam is oriented approximately 30" away from and parallel to the rotor chord, and perpendicular to the span axis. The Illuminator and the Tracker are supported on pivot axes and



TRANSPORTING MECHANISM

FIGURE 6



RANGE FINDER

FIGURE 7

toed-in, so that their optical axes intersect at the rotor surface. The Illuminator generates a .001" x .100" line of laser light on the rotor surface, with its long axis parallel to the rotor span axis. The Illuminator pivots at an angular rate of 1 degree per second, sweeping the line of light across the surface of the rotor. As the Illuminator pivots, the Tracker also pivots smoothly under computer control, to follow the line of light across the rotor surface. Residual tracking errors, due to unpredicted surface contour variations, are measured by an open loop sensor in the optical Tracker to an accuracy of ±.0005" over a range of ±.0500".

The laser Illuminator contains a helium-neon laser emitting 5 milliwatts of polarized light at 0.63282 micron wavelength in a 0.8 mm diameter beam with 1 milliradian beam divergence. The light path is folded by flat mirrors for system compactness and its diameter is expanded sixty times by an optical beam expander in order to reduce its divergence from 1000 microradians to 25 microradians in the direction perpendicular to the rotor span axis. In the direction parallel to the span axis, a hundred times larger beam divergence of 2500 microradians is generated by a cylindrical lens incorporated in the beam expander. The expander output is focused on the rotor surface by a servoed objective lens, so that it generates a .001" x .100" line image.

The contour tracker views the illuminated line on the rotor surface through a lens system consisting of a collimating objective lens and a servoed focusing objective lens. In the space between these two lenses, a square aperture stop is located with one pair of sides parallel to the line image on the rotor surface. This square stop (operating in conjunction with the two lenses near it) generates a rectangular pyramid of light flux in the Tracker. This pyramid converges toward a line-shaped apex parallel to the same two sides of the aperture stop; the apex is an image of the laser line on the rotor surface.

The rectangular pyramid of light is intercepted near its apex by a two-element silicon photodetector. The intersection of the photo detector plane with the flux pyramid is a rectangle of light with an intensity distribution which is bilaterally symmetrical. If the laser line moves off center in the field of view of the Tracker, the difference of the flux levels intercepted by the two silicon elements is a direct linear measure of the distance of the laser line from the center of the Tracker's field of view.

The optical geometry and detector configuration described above are key elements in this system. Its metrological integrity depends on the feasibility of establishing a stable relationship between the flux difference on the two detectors and the laser line position. We have selected a two-element silicon photo detector, because these detectors exhibit responsivities which change only about 0.1%/C°. Furthermore, these two-element silicon detectors are made as a unit; hence the individual detector elements have practically identical chemical and physical properties, and tend to track their cellmates in photo-detective responsivity. By way of comparison, photomultiplier detectors have responsivities which change approximately 1%/C°, and are individually made; hence, it would be difficult to get two photomultipliers to match in responsivity over the temperature range and effective operating lifetime required in this type of application.

7. ALIGNMENT AND CALIBRATION

In order to achieve the desired metrological accuracies, contours in the order of ±0.001" over a 48" chordal section, it was necessary to align the optical elements and calibrate the electronic elements to the following criteria:

Illuminator and Tracker angular position readouts to ±0.0001°.

Illuminator and Tracker spindle parallel to each other to ±0.01°.

Illuminator and Tracker optical axis perpendicular to their respective axes of rotation to ±0.01°.

The planes generated by the rotation of the Illuminator and Tracker optical axes when the Illuminator and Tracker are scanning are coplanar to ±0.01".

Relationship of Illuminator and Tracker optical axis to angular position fiduciary points is ±0.001°.

Wander of Illuminator and Tracker optical axis throughout the entire range of travel of each focus carriage to less than ±0.001°.

The horizontal axis of the detector cell is parallel to the plane generated by the Tracker optical axis as the Tracker rotates to ±1°.

The axis of the cylindrical lens is aligned such that the 0.100" vertical line generated by the Illuminator is parallel to the Illuminator's axis of rotation to ±1°.

The eccentricity of the Illuminator and Tracker optical axis relative to their respective axis of rotation is known to ±0.0005".

The dynamic focus positional requirements of the Illuminator and Tracker focus lenses are known to ±0.001".

8. ELECTRONIC DATA PROCESSING

Introduction

The electronic data processing subsystem was configured during Phase I of the program; the choice of system design was made with the assistance of Hughes Helicopter, taking into account the data processing requirement of a major helicopter manufacturer. The computer and peripherals chosen provide a system that will:

1. Perform the computations to measure the specified dimensions
2. Be easy to use
3. Be low in cost
4. Provide flexibility as requirements change

The system is sufficient to develop, modify and execute the required measurement programs and calibration programs.

The computer subsystem has the following features:

1. Capability of modifying existing or generating new measurement programs
2. Capability of storing several measurement programs
3. Operation communication through keyboard
4. Output will be printed on any desired format of 80 characters per line
5. Printing time is 8.3 seconds per line
6. Graphic display to show contours

Description

The Electronic Data Processing System, EDPS, consists of the following major items:

1. CROMEMCO System Three, which incorporates dual floppy disks, 48K memory and a Byte Saver Card."
2. Teletype Model 43 Keyboard Printer

3. Conrac 17" TV display
4. Intermediate Processor designed and built by Dreyfus-Pellman Corporation

Software

The CROMEMCO System is programmed in Basic and Machine code and the Intermediate Processor is programmed in Machine code.

Function

The major items of the EDPS perform the following functions:

1. CROMEMCO - (Host Computer)
    - Directs Rangefinder to contour the required points and/or section of the rotor blade automatically
    - Does triangulation mathematics and computes X-Y coordinates of rotor blade section
    - Rotates the mechanical or specification coordinates for best fit with the electro-optical coordinates; determines point-by-point differences and RMS difference
    - Provides human inputs to TV screen and printer

2. Teletype -
    - Provides input/outputs to system

3. Conrac TV -
    - Provides graphic display of electro-optical contour, mechanical/or specified contour, compares same, and shows difference between them

4. Intermediate Processor
    - Closes servo loops
    - Provides automatic focus computations

9. TESTS

This section describes the test performed using the prototype electro-optical rangefinder.

Contour Comparison

The purpose of these tests is to compare the contours generated by the electro-optical rangefinder to some other recognized contour of the same line on the same rotor blade. For the purpose of these tests, a Brown & Sharp Validator was used to determine the coordinates of points which defined a contour. This contour was then compared to the contour defined by the electro-optical rangefinder. In order to have a meaningful comparison, it is necessary that the same points be used to define the contour produced by the Validator and the electro-optical rangefinder. These measurements were accomplished as follows:

1. The rotor blade section was placed on the electro-optical rangefinder test stand and the Illuminator was directed to "paint" a horizontal scan line along its chord.
2. Four marks were placed along the chord of the rotor blade section to show the path of the Illuminator scan line. If one were to draw a line connecting these four marks, it would coincide with the Illuminator's scan line to within ±0.015".
3. A tape was placed approximately 1/4" above these four marks. This tape was then marked with vertical lines. The intersection of the downward projection of the vertical lines and the line connecting the four scan line marks represents the points which will be used to define contours.
4. The rotor blade section was then placed on the Validator Table in such a manner that, when the Validator stylus was at a fixed Z setting, it intersected all four scan line marks on the rotor blade.
5. The Validator stylus was then raised so that it intersected the vertical lines on the tape.

6. The Validator stylus was then moved to a specific line on the tape, its X position being locked, lowered to the predetermined Z position, checked for contact with the rotor blade section, and then its X, Y, Z coordinates were printed out to ±0.0001" readings. This was done for all of the points on the rotor blade section.
7. The rotor blade section was then placed on the Electro-optical Rangefinder test stand in the same position as it was in step 1 above, such that the Illuminator scan line passed through all four marks.
8. The Illuminator spot was moved so that it was directly below each vertical line on the tape to within ±0.015" and the Illuminator angle was recorded for each line position.
9. The Electro-optical Rangefinder was then directed, via the keyboard, to automatically determine the coordinates of sixteen points, spaced approximately 0.0003" apart and centered about each of the Illuminator angles determined in (8) above. This resulted in a group of sixteen electro-optically determined coordinates in close proximity to each Validator-determined coordinate.
10. All of the above data were entered into the computer and the following was accomplished:
    a) The slope between every other group of points was determined (between points 1 and 3, 2 and 4, 3 and 5, etc.).
    b) A straight line was drawn through each point having a slope identical to the slope determined in (a) above by the points surrounding the point through which the straight line was drawn.
    c) The contour formed by the intersection of the straight lines shown in (b) above is now a close approximation of the electro-optical contour.
    d) The distance between the mechanical coordinates and the contour determined in (c) above was calculated, and

e) The mechanical coordinates were rotated and translated for best fit with the electro-optical contour. This best fit was defined as the condition where the RMS value of the distances between the mechanical points and the electro-optical contour was at a minimum.

Repeatability Measurement

A rotor blade was contoured electro-optically, as in the contour comparison described above. It was then moved one inch along its chord and the average of sixteen electro-optical readings 0.001" apart, in the same location as the previously-determined electro-optical points, was taken. These new electro-optical coordinates were then best fitted, in a manner similar to the contour comparison, to the original electro-optical coordinates, differences were computed, and the RMS differences calculated.

Swept-Back Rotor Section Contour

In order to determine how well the Electro-optical Rangefinder will operate on a swept-back rotor such as the AAH, an AAH section was tilted 20° and a contour comparison was made as above.

Accuracy Measurements

In order to determine the absolute accuracy of the Electro-optical Rangefinder, a special test fixture was designed, built and then measured with traceability to the National Bureau of Standards. This fixture was then measured, using the Electro-optical Rangefinder. Both sets of measurements were compared.

The fixture consisted of an aluminum plate 40" x 6" x 1 1/2" upon which were mounted five one-inch diameter plug gages. The coordinates of the center of each plug gage were determined by Moore Special Tool Company to an accuracy of 20 microinches. Figures 8 and 9 are copies of the Certificate of Accuracy.

The Rangefinder was programmed to scan a contour line of approximately 90° on each plug gage. The center coordinates of each plug gage were computed from the respective contour date.

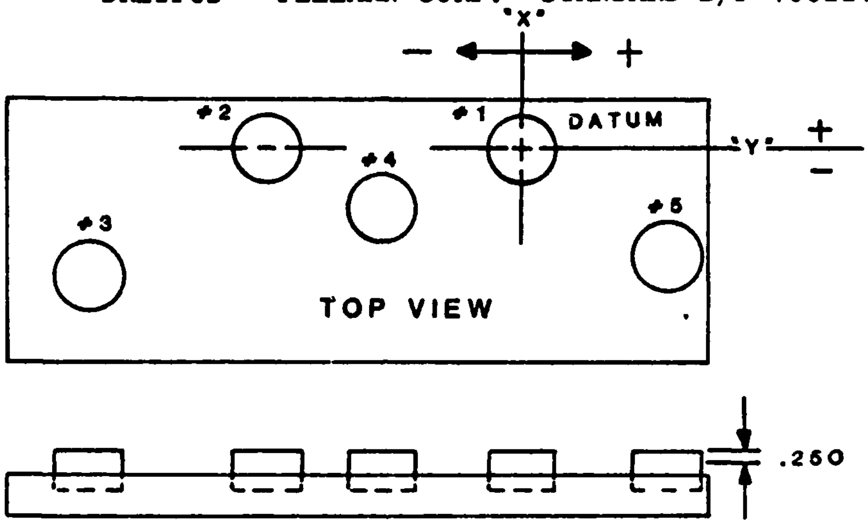
The coordinates determined by the Rangefinder were then rotated and translated to match the coordinate system of the fixture as specified on the Certificate of Accuracy. The difference of coordinates of each plug gage center were then determined and tabulated.

Moore Special Tool Co., Inc.

Certificate of Accuracy

OF

DREYFUS - PELLMAN CORP. STANDARD B/P 100224



Line up #1 and #2. Datum is on #1.

All readings are taken .250 down from top of pins as shown.

	"X"	"Y"
1.	.00000	.00000
2.	-23.99901	.00000
3.	-34.99841	-2.49975
4.	-13.99984	-1.24980
5.	+ 4.99948	-1.25017

Positions shown above were calibrated on the Moore Universal Measuring Machine S/N 5001 @ 68°F 40% Relative Humidity.

It is estimated that the reported values are accurate to ± 20 micro-inches.

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Figure 8

Moore Special Tool Co., Inc.

Certificate of Accuracy

OF

DREYFUS - PELLMAN CORP. STANDARD B/P 100224

This machine was calibrated January 5, 1979 and is traceable to National Bureau of Standards Test No. 232.12/212228.

Calibrated By: Raymond Giordano
Supervisor, Contract Measuring

Approved By: Richard L. Parnoff
Manager, Quality Control

Date: March 8, 1980

Certification #907

Page 2 of 2

Figure 9

10. TEST RESULTS

Figures 10 thru 14 are computer printouts of the results of the contour comparison tests made during this phase of the program. The results of these tests show that the electro-optical contours obtained differ from the mechanical contours by as little as 0.0016" and as much as 0.0026".

The following tabulation shows the results of the accuracy measurements.

Certificate Data		Rangefinder Measurement		Difference	
X	Y	X	Y	X	Y
.00000	.00000	.00012	- .00027	.00012	.00027
-23.99901	.00000	-23.99812	- .000373	.00089	-.00373
-34.99841	-2.49975	-34.99842	-2.49967	- .00001	.00008
-13.99984	-1.24980	-13.99652	-1.24657	.00332	.00323
4.99948	-1.25017	4.99948	-1.25017	0	0

Figure 10

	DIRECT	MIRROR	DIM.
BL	40.0000	32.1848	INCHES
IOI	75.3813	13.7389	DEGREES
IOT	42.7471	50.1387	DEGREES
EI	-.0683	.0683	INCHES
ET	.0340	.0340	INCHES

P#	VIEW	IL	TR	XEO	YEO	XM	YM	DIST
1	M	48.1980	25.9232	25.9454	38.9582	25.9322	38.9755	.0035
2	M	48.3793	25.7025	26.0246	38.8101	25.9832	38.8871	-.0196
3	M	48.6731	25.4417	26.2099	38.6563	26.1817	38.7081	-.0271
4	D	49.0254	27.8376	26.4612	38.5150	26.4311	38.5713	-.0364
5	D	49.2391	28.0218	26.6246	38.4450	26.6017	38.4882	-.0310
6	D	49.5722	28.3162	26.8822	38.3389	26.8598	38.3843	-.0347
7	D	49.8831	28.6160	27.1342	38.2552	27.1204	38.2964	-.0353
8	D	50.2084	28.9467	27.4055	38.1767	27.3887	38.2167	-.0337
9	D	50.5094	29.2560	27.6574	38.1037	27.6394	38.1483	-.0383
10	D	50.8195	29.5899	27.9238	38.0363	27.9138	38.0809	-.0412
11	D	51.1102	29.9217	28.1824	37.9835	28.1594	38.0281	-.0389
12	D	51.3882	30.2358	28.4275	37.9279	28.4111	37.9779	-.0465
13	D	51.6586	30.5836	28.6870	37.9004	28.6659	37.9324	-.0293
14	D	51.9283	30.9243	28.9421	37.8661	28.9159	37.8929	-.0231
15	D	52.1535	31.2151	29.1580	37.8398	29.1293	37.8641	-.0206
16	D	52.3892	31.5220	29.3850	37.8118	29.3426	37.8384	-.0221
17	D	53.2132	32.6451	30.2015	37.7308	30.1768	37.7499	-.0165
18	D	54.6702	34.7336	31.6882	37.5895	31.6554	37.5933	-.0015
19	D	55.9972	36.8768	33.1610	37.5390	33.1313	37.5390	.0006
20	D	57.1174	38.8398	34.4833	37.5327	34.4516	37.5354	-.0033
21	D	58.3755	41.2401	36.0761	37.5779	36.0572	37.5778	-.0007
22	D	59.4722	43.5004	37.5641	37.6600	37.5330	37.6544	.0033
23	D	60.4562	45.6810	38.9973	37.7784	38.9775	37.7768	-.0003
24	D	61.4614	48.0768	40.5798	37.9567	40.5530	37.9531	.0001
25	D	62.2983	50.2052	42.0018	38.1536	41.9814	38.1494	.0014
26	D	63.1465	52.4426	43.5195	38.3740	43.5037	38.3754	-.0038
27	D	63.9543	54.6606	45.0547	38.6144	45.0334	38.6112	-.0002
28	D	64.7504	56.9065	46.6462	38.8694	46.6397	38.8678	.0006
29	D	65.4884	59.0206	48.1824	39.1111	48.1632	39.1087	-.0006
30	D	66.1584	60.9640	49.6321	39.3358	49.6112	39.3301	.0025
31	D	66.8232	62.9049	51.1192	39.5592	51.1130	39.5602	-.0019
32	D	67.4844	64.8686	52.6730	39.8002	52.6630	39.8002	-.0014
33	D	68.0355	66.5215	54.0233	40.0116	54.0122	40.0114	-.0012
34	D	68.5294	67.8742	55.1250	40.0976	55.1254	40.0958	.0018

DISTANCE RMS = .0018

Contract: DAAK 50-78-C-0024

Item: 4

Blade Section Cobra Composite

Electro-Optical Data Compared to Mechanical Data.

Points 1 through 17 fall on the rubber portion of this blade section. Points 18 through 34 fall on the fiberglass portion.

When making mechanical measurements using the Validator there was considerable dig in on the rubber surface. It is felt that this dig in is of sufficient magnitude to invalidate these mechanical measurements as a standard of compairison. Therefore, they are excluded from the RMS calculation and are presented for information only.

Contract: DAAK 50-78-C-0024

Item: 4

Blade Section Bell 214 015 001

Electro-Optical Data Compared to Mechanical Data

	DIRECT	MIRROR	DIM.
BL	40.0000	32.1848	INCHES
IOI	75.3813	13.7389	DEGREES
IOT	42.7471	50.1387	DEGREES
EI	-.0683	.0683	INCHES
ET	.0340	.0340	INCHES

PN	VIEW	IL	TR	XEO	YEO	XM	YM	DIST
1	M	48.2566	25.9162	26.0107	38.9698	26.0031	38.9907	-.0031
2	M	48.3951	25.7476	26.0713	38.8567	26.0598	38.8689	.0026
3	M	48.5501	25.5897	26.1567	38.7568	26.1377	38.7725	.0032
4	M	48.7004	25.4470	26.2453	38.6690	26.2244	38.6857	.0012
5	M	49.0296	25.1585	26.4529	38.4969	26.4323	38.5173	-.0038
6	M	49.1882	25.0340	26.5626	38.4281	26.5468	38.4393	-.0013
7	M	49.5095	24.7891	26.7869	38.2918	26.7752	38.3019	-.0032
8	M	49.8285	24.5680	27.0231	38.1754	27.0039	38.1848	-.0003
9	M	50.1353	24.3638	27.2554	38.0697	27.2370	38.0766	.0013
10	M	50.4344	24.1689	27.4840	37.9689	27.4710	37.9787	-.0042
11	M	50.7363	23.9879	27.7253	37.8805	27.7142	37.8847	-.0002
12	M	51.0445	23.8098	27.9759	37.7950	27.9523	37.7996	.0030
13	M	51.3575	23.6333	28.2336	37.7107	28.2187	37.7145	.0008
14	M	51.6463	23.4824	28.4802	37.6434	28.4607	37.6445	.0041
15	M	51.8334	23.3829	28.6387	37.5973	28.6144	37.6031	.0006
16	M	52.0214	23.2893	28.8029	37.5566	28.7903	37.5575	.0018
17	M	52.4345	23.0926	29.1708	37.4740	29.1513	37.4745	.0028
18	D	54.1132	33.2756	30.7692	37.2260	30.7563	37.2261	.0012
19	D	55.9684	36.1486	32.7509	37.1110	32.7495	37.1138	-.0027
20	D	57.6526	39.1348	34.7408	37.1107	34.7381	37.1170	-.0062
21	D	59.1884	42.1753	36.7298	37.1884	36.7306	37.1924	-.0040
22	D	60.6172	45.2480	38.7281	37.3063	38.7274	37.3080	-.0018
23	D	61.9464	48.3084	40.7240	37.4497	40.7241	37.4485	.0012
24	D	63.1864	51.3450	42.7254	37.6193	42.7276	37.6161	.0034
25	D	64.3223	54.2826	44.6968	37.8113	44.6978	37.8099	.0015
26	D	65.3865	57.1704	46.6838	38.0299	46.6902	38.0320	-.0014
27	D	66.3683	59.9563	48.6632	38.2766	48.6720	38.2761	.0016
28	D	67.2854	62.6372	50.6388	38.5370	50.6466	38.5370	.0011
29	D	68.1475	65.2208	52.6228	38.8130	52.6281	38.8146	-.0008
30	D	68.9204	67.6370	54.5764	39.1306	54.5886	39.1313	.0013
31	D	69.6512	69.9503	56.5409	39.4593	56.5625	39.4641	-.0015
32	D	70.3945	72.2015	58.5165	39.7213	58.5270	39.7238	-.0025

DISTANCE RMS = .0026

Figure 11

Contract: DAAK 50 -78-C-0024

Item: *4*

Blade Section Hughes AAH

Electro-Optical Data Compared to Mechanical Data

	DIRECT	MIRROR	DIM.
BL	40.0000	32.1848	INCHES
IOI	75.3813	13.7389	DEGREES
IOT	42.7471	50.1387	DEGREES
EI	-.0683	.0683	INCHES
ET	.0340	.0340	INCHES

PN	VIEW	IL	TR	XEO	YEO	XM	YM	DIST
1	M	48.2721	25.8380	25.9816	38.9033	25.9639	38.9214	.0008
2	M	48.4634	25.6477	26.0900	38.7845	26.0661	38.8034	.0014
3	M	48.6913	25.4589	26.2421	38.6774	26.2247	38.6874	.0000
4	M	49.0723	25.1845	26.5208	38.5343	26.5069	38.5425	-.0016
5	M	49.3664	24.9953	26.7497	38.4430	26.7325	38.4517	-.0023
6	M	49.6610	24.8223	26.9887	38.3644	26.9740	38.3736	-.0049
7	D	49.9445	28.7712	27.2322	38.3066	27.2090	38.3121	-.0003
8	D	50.2083	29.0625	27.4641	38.2587	27.4618	38.2615	-.0023
9	D	50.4831	29.3813	27.7128	38.2173	27.6993	38.2201	-.0006
10	D	50.7625	29.7097	27.9673	38.1755	27.9540	38.1800	-.0025
11	D	51.0175	30.0225	28.2059	38.1441	28.1906	38.1478	-.0021
12	D	51.2851	30.3688	28.4650	38.1211	28.4517	38.1217	.0005
13	D	51.5353	30.6989	28.7102	38.1016	28.6931	38.1026	.0002
14	D	51.7862	31.0423	28.9621	38.0881	28.9531	38.0869	.0017
15	D	52.0344	31.3869	29.2136	38.0757	29.2080	38.0752	.0008
16	D	52.2803	31.7343	29.4656	38.0651	29.4497	38.0666	-.0012
17	D	52.8005	32.5083	30.0184	38.0610	30.0020	38.0591	.0018
18	D	53.7084	33.9315	31.0194	38.0750	31.0080	38.0749	-.0003
19	D	54.5602	35.3765	32.0162	38.1283	32.0004	38.1263	.0010
20	D	55.3782	36.8413	33.0157	38.1992	33.0029	38.2015	-.0034
21	D	56.1583	38.3248	34.0184	38.2943	34.0205	38.2983	-.0037
22	D	56.8874	39.8184	35.0200	38.4271	35.0093	38.4270	-.0014
23	D	57.6143	41.4030	36.0797	38.5966	36.0710	38.5979	-.0027
24	D	58.2204	42.7933	37.0108	38.7638	36.9971	38.7625	-.0012
25	D	58.8382	44.2712	38.0049	38.9567	37.9946	38.9538	.0008
26	D	59.4093	45.7161	38.9831	39.1721	38.9751	39.1716	-.0013
27	D	59.9444	47.1391	39.9557	39.4080	39.9582	39.4073	.0013
28	D	60.4525	48.5542	40.9350	39.6654	40.9280	39.6637	-.0002
29	D	60.9304	49.9405	41.9088	39.9381	41.9132	39.9391	.0002
30	D	61.4052	51.3340	42.9034	40.2142	42.8985	40.2141	-.0012
31	D	61.8334	52.6167	43.8346	40.4773	43.8464	40.4797	.0007
32	D	62.4064	54.2619	45.0468	40.7714	45.0468	40.7713	.0001
33	D	63.1463	55.8972	46.2329	40.7726	46.2270	40.7730	-.0004

Figure 12

Contract: DAAK 50-78-C-0024

Item: 0001AB

Blade Section Bell 214 015 001
Electro-Optical Data Taken With Section in Normal Position and in Position One Inch From Normal.. Data Compared

	DIRECT	MIRROR	DIM.
BL	40.0000	32.1848	INCHES
IOI	75.3813	13.7389	DEGREES
IOT	42.7471	50.1387	DEGREES
EI	-.0683	.0683	INCHES
ET	.0340	.0340	INCHES

PN	VIEW	IL(1)	TR(1)	XEO(1)	YEO(1)	XEO(2)	YEO(2)	DIST
1	M	48.2562	25.9153	26.0104	38.9699	25.9999	38.9775	.0056
2	M	48.3954	25.7480	26.0717	38.8569	26.0687	38.8599	.0009
3	M	48.5504	25.5845	26.1536	38.7519	26.1511	38.7576	-.0020
4	M	48.7003	25.4453	26.2442	38.6675	26.2380	38.6670	.0044
5	M	49.0295	25.1564	26.4520	38.4957	26.4453	38.5011	-.0002
6	M	49.1885	25.0315	26.5612	38.4257	26.5531	38.4304	.0001
7	M	49.5094	24.7901	26.7875	38.2928	26.7808	38.2996	-.0028
8	M	49.8285	24.5651	27.0212	38.1727	27.0168	38.1791	-.0039
9	M	50.1352	24.3621	27.2542	38.0682	27.2480	38.0744	-.0032
10	M	50.4342	24.1665	27.4823	37.9669	27.4781	37.9748	-.0058
11	M	50.7364	23.9842	27.7228	37.8771	27.7202	37.8808	-.0027
12	M	51.0446	23.8071	27.9735	37.7915	27.9652	37.7896	.0044
13	M	51.3575	23.6309	28.2320	37.7086	28.2258	37.7119	-.0015
14	M	51.6466	23.4801	28.4782	37.6402	28.4691	37.6388	.0039
15	M	51.8333	23.3823	28.6382	37.5966	28.6323	37.5999	-.0017
16	M	52.0211	23.2870	28.8010	37.5544	28.7908	37.5596	-.0028
17	M	52.4343	23.0930	29.1710	37.4745	29.1586	37.4732	.0034
18	D	54.1133	33.2776	30.7703	37.2272	30.7578	37.2256	.0030
19	D	55.9683	36.1500	32.7516	37.1120	32.7359	37.1122	.0003
20	D	57.6523	39.1359	34.7413	37.1117	34.7307	37.1134	-.0019
21	D	59.1883	42.1775	36.7311	37.1900	36.7188	37.1890	.0002
22	D	60.6176	45.2503	38.7295	37.3072	38.7214	37.3074	-.0008
23	D	61.9463	48.3098	40.7249	37.4507	40.7127	37.4520	-.0023
24	D	63.1862	51.3465	42.7265	37.6207	42.7136	37.6170	.0025
25	D	64.3222	54.2845	44.6982	37.8128	44.6868	37.8074	.0042
26	D	65.3863	57.1718	46.6849	38.0311	46.6745	38.0319	-.0020
27	D	66.3682	59.9573	48.6641	38.2774	48.6564	38.2784	-.0020
28	D	67.2854	62.6389	50.6403	38.5382	50.6256	38.5360	.0003
29	D	68.1475	65.2241	52.6260	38.8154	52.6112	38.8145	-.0013
30	D	68.9203	67.6383	54.5779	39.1318	54.5704	39.1323	-.0018
31	D	69.6514	69.9519	56.5426	39.4601	56.5377	39.4603	-.0009
32	D	70.3942	72.2007	58.5158	39.7213	58.5186	39.7230	-.0017

DISTANCE RMS = .0028

Figure 13

Contract: DAAK 50-78-C-0024

Item: 0001AB

Blade Section Hughes AAH Tilted 20°
Electro-Optical Data Compared to Mechanical Data

	DIRECT	MIRROR	DIM.
BL	40.0000	32.1848	INCHES
IOI	75.3813	13.7389	DEGREES
IOT	42.7471	50.1387	DEGREES
EI	-.0683	.0683	INCHES
ET	.0340	.0340	INCHES

PN	VIEW	IL	TR	XEO	YEO	XM	YM	DIST
1	M	48.0277	26.4542	26.0703	39.4002	26.0714	39.4006	-.0012
2	M	48.1501	26.2993	26.1217	39.2950	26.1191	39.2938	.0029
3	M	48.3071	26.1253	26.2013	39.1814	26.2062	39.1817	-.0036
4	M	48.6545	25.8248	26.4284	39.0069	26.4362	38.9977	.0028
5	M	48.7725	25.7298	26.5097	38.9539	26.5107	38.9531	.0001
6	M	49.0672	25.5085	26.7223	38.8354	26.7407	38.8262	-.0002
7	M	49.3572	25.3068	26.9411	38.7322	26.9446	38.7291	.0014
8	M	49.6661	25.1032	27.1810	38.6313	27.1895	38.6319	-.0034
9	M	49.9671	24.9274	27.4295	38.5528	27.4410	38.5486	.0006
10	M	50.2682	24.7560	27.6812	38.4770	27.6865	38.4786	-.0029
11	M	50.6003	24.5832	27.9701	38.4073	27.9808	38.4013	.0033
12	M	50.8322	24.4588	28.1697	38.3543	28.1796	38.3532	-.0012
13	M	51.0963	24.3277	28.4046	38.3031	28.4161	38.2984	.0022
14	M	51.3644	24.1994	28.6469	38.2547	28.6638	38.2527	-.0012
15	M	51.5961	24.0928	28.8602	38.2167	28.8834	38.2159	-.0028
16	M	51.8943	23.9667	29.1434	38.1772	29.1534	38.1759	-.0001
17	M	52.4063	23.7515	29.6333	38.1086	29.6463	38.1065	.0005
18	M	52.9335	23.5452	30.1532	38.0501	30.1662	38.0462	.0024
19	M	53.1563	23.4583	30.3746	38.0251	30.3891	38.0234	.0003
20	M	53.5024	23.3332	30.7279	37.9949	30.7367	37.9919	.0024
21	M	53.9794	23.1597	31.2177	37.9507	31.2352	37.9527	-.0018

DISTANCE RMS = .0021

Figure 14

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11. DISCUSSION OF RESULTS

The objective of Phase 2 of this program was to build and test a prototype Electro-optical Rangefinder that could be used in a prototype system to measure the contours of full-size helicopter rotor blades to accuracies of 0.001".

Contour measurements were made, using the prototype rangefinder, and compared to those made using a Brown & Sharpe Validator. The differences between these two contours was in the order of 0.0016" to 0.0026". The following factors contribute to these differences:

1. Mechanical Measurement Accuracy. The Validator used to measure the contours of these blade sections had an assumed accuracy of 0.0003" to 0.0005".

2. Instability of Blade Sections. The blade sections are rather flexible, and it is doubtful that their contours remained stable between mechanical and electro-optical measurements to better than 0.001".

3. Clamping of Blade Sections. During mechanical contouring, the blade sections were clamped. During electro-optical contouring, the blade sections were freestanding. This might have produced distortions of up to 0.0015".

4. Different Points Being Measured to Obtain Contours. The mechanical contours and electro-optical contours were made on different machines and in different facilites. It was impossible to assure that the exact same points were measured both times. At best, the points measured on each occasion differed in position by 0.005".

5. Optical Phenomenon. Measurement errors of the electro-optical system were caused by non-uniformity of light reaching the Tracker. This was due to lobing and mottling of the light as it left the rotor blade section. This phenomenon is a function of aspect angle and surface characteristics.

Dreyfus-Pellman has several suggested modifications to the tracker which would reduce the effect of this phenomenon on accuracy and would like to implement them during Phase 3 of the overall program when it is funded.

In general, the tests performed on the prototype system indicate that the basic concept is sound, and that a full-scale system is feasible.

The accuracy measurement data shows that accuracies in the order of 0.001" to 0.002", traceable to the National Bureau of Standards, can be obtained.