Holographic Testing of Composite Propfans for a Cruise Missile Wind Tunnel Model

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SUMMARY

Each of the approximately 90 composite propfan blades constructed for a 55 percent scale cruise missile wind tunnel model were holographically tested to obtain natural frequencies and mode shapes. These data were used not only for quality assurance, but also to select sets of similar blades for each blade row. Presented along with the natural frequency data is a description of a computer-based image processing system developed to supplement the photographic-based system for holographic image analysis and storage. The new system is quicker and cheaper, the holograms are indexed better, and several engineers can access the data simultaneously. The only negative effect is a slight reduction in image resolution, which does not influence the end use.

BACKGROUND

NASA Lewis Research Center uses holographic bench testing of turbomachinery components to obtain the components' natural mode shapes and frequencies. On the bench, the parts are excited via an acoustic driver which controls amplitude and a range of frequencies. These data are used to verify the dynamic characteristics and quality of fabricated components. These natural mode data are also used in the design process so that the final design part has the maximum safe operating envelope (considering integer order crossings and flutter boundaries).

The propfan blades, designed and constructed for a 55 percent scale wind tunnel model of a cruise missile, were constructed of composites instead of metal to meet wind tunnel safety requirements. Figure 1 shows a view of the lower tip speed blades, while figure 2 shows the higher tip speed blades. The blades used in this test were the first major composite fabrication project completed in-house. As a result, there were concerns about the repeatability and quality of the fabrication process as well as the accuracy of the structural modeling of the all composite parts. This report will present the holography data: natural frequencies for the first two bending and first two torsion modes, summaries of the frequencies presented as nondimensional differences from the mean values, and details of the computerized testing process. The analytic predictions corresponding to these data are presented in references 1 and 2. Details of the construction of the composite blades are documented in references 3 and 4.

Because so many holograms were desired (90 blades with at least 9 modes per blade for a total of over 810 images) a new holographic image process was developed to augment the existing photographically-based system. The new system, which consists of a video camera, digital frame grabber, and a computer for image processing, is not only faster and cheaper but also improves the engineers’ ability to use the data. An overview of this system is shown in figure 3, with details discussed in appendix A.

MEASURED FREQUENCIES

The blade frequencies of interest for integer order crossing comparisons are the first two bending and first two torsional modes, denoted as 1B, 2B, 1T, and 2T respectively. These frequencies are summarized in tables I
and II for CM1D (Cruise Missile blade, design 1, version D) forward and aft blades, and tables III and IV for CM2D.

For most of the blades, the measured frequencies are very consistent. The standard deviation for each natural frequency was calculated and is a small fraction of the mean, usually about 1 percent. For use in the wind tunnel experiment, sets of blades with similar frequency characteristics are desirable. To help in selecting these sets, plots of blade frequency by mode were generated along with a summary plot with normalized frequencies for all four modes of interest. To put all modes on a single summary plot, the frequencies for each mode were normalized using the mean and standard deviation

\[ \bar{f} = (f - \bar{f})/\sigma \]

where

\[ \bar{f} = \text{normalized natural frequency} \]
\[ f = \text{measured natural frequency} \]
\[ \bar{f} = \text{mean natural frequency} \]
\[ \sigma = \text{standard deviation of the natural frequency} \]

One of the criteria for selecting blade sets was consistency of the frequencies; a "good" blade has all frequencies clustered together on the summary plot, while a "bad" blade would have one or more frequencies significantly different from the others. When a blade had frequencies that fell more than two standard deviations away from the mean, it was considered flawed and not used as part of a flight set. A blade set consists of six blades for initial installation, with two similar blades as spares.

Due to integer order crossings and flutter considerations for these blades, the significance of an outlying mode was prioritized as 1B, 1T, 2B, and 2T. Once the blades were roughly grouped, the holograms were checked to verify mode shape similarity for the first four modes. Finally, the blade sets were grouped by frequencies and the highest frequency blade sets were used first to give the most integer order clearance. Within each blade set (including spares) the variation of natural frequencies was less than 1 percent.

During wind tunnel testing, two blades displayed obvious frequency changes from fatigue damage, a "ping" of the blade with a coin or finger produced a ringing sound that was qualitatively deader than that produced by pinging the other blades. These blades were removed from the model and retested to measure the change in frequencies and mode shapes. The fatigued blade frequencies are also listed in tables I and II.

Natural frequency plots are presented in figures 4 to 23. The individual mode frequency plots (1B, 1T, 2B, 2T) are shown first for each blade design: CM1D forward in figures 4 to 7, CM1D aft in figures 8 to 11, CM2D forward in figures 12 to 15, and CM2D aft in figures 16 to 19. The summary plots showing all frequencies for modes of all blades of each design are in figures 20 to 23 for CM1DF, CM1DA, CM2DF, and CM2DA respectively.

Representative mode shapes (113, 1T, 2B, 2T) for each for the four blade designs are shown in figures 24 to 27. In these composite images, the images are arranged by increasing mode frequency with the lowest
frequency mode in the bottom left, the next in the bottom right, the next in the top left, and the highest frequency mode in the top right. For the CM1D blades the order of increasing mode frequency is (1B, 2B, 1T, 2T) while for the CM2D blades the order is (1B, 1T, 2B, 2T). The mode shapes of the fatigued blades change slightly and are shown in figures 28 (CM1DF022) and 29 (CM1DA008). The higher frequency modes show the greatest change.

CONCLUDING REMARKS

Each of the composite propfan blades designed and constructed for a model scale cruise missile wind tunnel test program was holographically tested. The natural frequencies and mode shapes for the first eight blade modes were determined. These data were used to correlate with the structural analyses and verify the quality of the blades, as well as to select blade sets for the wind tunnel model.

During this work a computer-based image processing system was implemented to supplement a photographically-based system. The new system has these advantages

1. Holographic images are delivered to the requester within hours after they have been taken.

2. The holograms have the relevant test conditions stamped on the image to simplify the correlation with the test log.

3. Several engineers can access the images and data simultaneously.

4. The problems with filing/refiling time and space for the photos have been eliminated.

5. It is cheaper, not only in creating the image but in any subsequent hard copy.

The only negative effect is a slight reduction in image resolution, which does not influence the end use.

ACKNOWLEDGMENT

The author would like to thank Mr. Kenneth Weiland for his help in teaching him the mechanics of creating a hologram and patience during the development of the software for this project.
APPENDIX A—COMPUTER BASED HOLOGRAPHIC IMAGE PROCESSING

OVERVIEW

Photographic holograms, the traditional method, are time consuming but are very high quality (fig. 30). When image resolution is not a high priority, a new computer-based system can provide holograms quickly and at a lower cost. The computer-based system has the additional advantages of requiring much less storage space, improving the indexing and retrieval process, and enabling several engineers to access the data at the same time.

BACKGROUND

The traditional technique for obtaining the holograms of mode shapes is a multiple step process.

<table>
<thead>
<tr>
<th>Step</th>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>5 min</td>
<td>Paint the model with titanium dioxide paint for good reflectivity.</td>
</tr>
<tr>
<td>(2)</td>
<td>2 min</td>
<td>Mount the blade on the bench (fig. 3).</td>
</tr>
<tr>
<td>(3)</td>
<td>3 min</td>
<td>Expose and develop the reference hologram. The reference hologram, placed in front of the camera, will create an interference fringe pattern with the laser light reflected from the vibrating blade.</td>
</tr>
<tr>
<td>(4)</td>
<td>1 min</td>
<td>Search for a vibration mode with the acoustic driver. This involves scanning the frequency until a mode is observed, through the TV camera in the film holder, by changes in the fringe pattern.</td>
</tr>
<tr>
<td>(5)</td>
<td>3 min</td>
<td>With the part vibrating, expose and develop the time average hologram.</td>
</tr>
</tbody>
</table>

Steps (4) and (5) are repeated for each vibration mode of interest.

(6) 5 min Expose a photographic negative.

(7) ? days Send the photographic negatives to the photo lab for developing and making 8- by 10-in. prints.

The need for photographic negatives, the delay in processing through the photo lab, the filing and indexing difficulties, and the large number of holograms to create indicated a need for a new technique.

COMPUTER-BASED IMAGE PROCESSING

Since the holography system uses a video camera for the detection of the vibration modes, incorporating a PC-based frame grabber was a simple step. The video camera shown in figure 3 remains connected to the monitor for mode searching, but it is also connected to the frame grabber in the PC. The frame grabber currently being used has a resolution of 480 scan lines by 512 pixels per scan line. Each pixel can be scanned as eight bits in each of the red, green, and blue channels. Since this is a black and white camera, only one channel is scanned. A scanned image is therefore 512 by 480 pixels with 256 possible gray levels available per pixel; uncompressed, the data for the image itself totals 245,760 bytes.
The photographic process has a much finer spacial resolution than the frame grabber's 512 by 480, but this level of detail is not needed here. Similarly, the 256 gray levels are more than adequate for mode shape verification.

The computer allows for additional functionality over the photographic system since each image is stamped with a descriptive name and the relevant test data before it is saved. The images are thereby much easier to track and correlate with the test log.

Once a series of images has been obtained and stored on the PC, the images can be studied on the PC, or transferred over the local ethernet network to a workstation for the added processing power and storage available there. The workstation is also the access point for the archival storage system for computer data.

**IMAGE PROCESSING STEPS**

The processing of the images involves basically three steps.

1. Determine the sub-range, within 0 to 255, that contains the useful data.
2. Create the single mode images.
3. Create a combined image of all modes for a given blade.

Custom software was developed to operate the frame grabber board, see appendix B and reference 5. This software currently has no contrast or brightness controls. Instead, a set of default settings are used that are conservative enough to prevent pixel value clipping. Due to the variability of the holographic imaging process, these default settings produce images with a fair amount of background noise and a dynamic range that is less than full scale. Besides automatic scaling, multiple frames could be averaged to create a time average hologram. The averaging improves the pixel signal/noise ratio.

The first processing step identifies the portion of the data range that produces the subjectively best image. This can be done iteratively for each image but a good algorithm is to select for the low end the pixel value such that 25 percent of the total pixel population lies below, and for the upper end such that 95 percent of the pixels lie below. In the PC program that calculates the histogram for an image (appendix B), this scheme is used to recommend processing limits (fig. 31). In the PC program that displays the images (appendix C), this scheme is used for the default scaling prior to display.

For each blade, ten images were created: the reference image, eight mode images, and one composite image. The sub-range expansion and single mode image creation can be done on the PC, but were usually performed on a workstation to off-load the PC. Figure 32 shows a raw image without the sub-range image expansion. Figure 33 shows the processed image enhanced with sub-range expansion.

The composite image is composed of the reference image and the eight mode images in a 3 by 3 array. The individual images are reduced from their original 512 by 480 size to 256 by 240 prior to the assembly step. The composite image size is then 768 by 720 pixels. Figure 34 shows a representative composite image. Once images have been created, they can be studied on the computer or, if a hardcopy is needed, they can be printed on a laser printer. This hardcopy method is much cheaper and easier than making the traditional 8- by 10-in. photographic prints.
The images were originally stored on the workstation in a "run-length encoded" format and then compressed with the UNIX (tm) "compress" utility to further reduce their size. The total storage needed for the images of all blades is approximately 140 MB. The size of the images (as well as the total storage needed) is a major problem for the PC-based image processing scheme. During the holography, the images rapidly fill the hard disk on the PC and require substantial time to off-load.

An alternative storage scheme considered is GIF (Graphic Interchange Format, (c) CompuServe), which includes an internal Lempel-Zif-Welch compression scheme and can store images with up to 256 unique colors (or 256 levels of grey-scale). As noted in table VII, both schemes achieve about the same compression. For grey-scaled images stored in a format that preserves all the pixel information, this is about as compressed as possible. Since the actual pixel values in the image are qualitative rather than quantitative, a compression scheme that loses some information in exchange for greater compression can be used.

The Joint Photographic Experts Group (JPEG) scheme (ref. 6) is one such lossy technique. The heart of the JPEG scheme is the use of a Discrete Cosine Transform on patches of the image. As the quality level is increased, more of the high order, high spatial frequency coefficients are included. For images with smooth spatial variations, only a few coefficients need to be saved, resulting in a large compression ratio with a corresponding increase in the loss of high spatial frequency information. In the holographic images, high JPEG compression (low Q factors) primarily introduces errors at the edges of the labels stamped on to the images.

Table VII summarizes the compression ratios achieved with the various schemes, as well as the JPEG scheme with varying loss factors. Subjectively evaluating the images as displayed on the computer reveals that the image compressed with JPEG at Q = 50 looks to the eye like the original image. Even more interesting is that the original image printed in 16 grey levels (fig. 29) looks the same as one compressed with JPEG at Q = 20 in a 16 grey level print (fig. 30).

If JPEG compression at Q = 50 is used to process all the images, the total storage needed would drop from 140 MB down to approximately 8 MB, removing the storage problems of the PC computer-based technique.
PROGRAM DRVPPI
C C SIMPLE DRIVER PROGRAM FOR THE PIP BOARD C C THIS IS A GENERIC PROGRAM TO TAKE HOLOGRAPHIC IMAGE DATA C C 910204 CHRISTOPHER J. MILLER C C****************************************************************************** C IMPLICIT INTEGER (A-E) IMPLICIT REAL (F) IMPLICIT INTEGER (G-Z) C INTEGER*4 IHISTO C INTEGER*2 DECODE C C CHARACTER STRING*21, FNAME*13, DATSTR*9 C CHARACTER TIMSTR*9 C CHARACTER IMGLBL*8, ANS*1 C INTEGER I C INTEGER*2 IVAL C INTEGER FREQ, VOLT C CHARACTER BUFFER(4096) C C interpreter commands: C inifmt 26c 1 0 0 0 0 C setind 255 C chan 2 C sync 1 C quadmode 4
IVAL = INIFMT(620, 1, 0, 0, 0, 0) IF (IVAL.NE.1) THEN
PRINT *, 'PIP board not found; return value =', I
STOP ENDIF
IVAL = IWINMD(0)
CALL SETWIN(0, 0, 511, 511)
CALL SETIND(255)
CALL SYNC(1)
CALL CHAN(2)
CALL DELAY(5)
C C Setup: select a good gain and offset
CALL AUTO
CALL CLEAR(0,7)
CALL SNAP(1)
PRINT *, 'Do you want to set the gain and offset?'
READ (5,*) ANS
IF (ANS.EQ.'Y' .OR. ANS.EQ.'y') CALL SETUP
C C LOOP FOR TAKING DATA
100 CONTINUE
PRINT *
WRITE(6,1000)
1000 FORMAT(' I ......
I UNIQUE LABEL (FILE NAME) FOR MODE IMAGES')
READ (5,'(1A8)') IMGLBL
CALL UPCASE(IMGLBL)
PRINT *
C C MODE LOOP
105 CONTINUE
WRITE(6,1010)
1010 FORMAT('$, MODE (-1 TO QUIT) : ')
READ (5,*) MODE
IF (MODE.LT.0) GOTO 150
C PRINT *, 'PRESS ENTER WHEN THE IMAGE IS READY'
READ (5,*)


CALL CLEAR(0,7)
CALL SNAP(1)

C GET THE FREQUENCY AND VOLTAGE
WRITE(6,1020)
1020 FORMAT($,' ENTER THE FREQUENCY: ')
READ (5,*) FREQ
WRITE(6,1030)
1030 FORMAT($,' ENTER THE VOLTAGE: ')
READ (5,*) VOLT

C GENERATE THE FILE NAME
C LABEL THE IMAGE WITH THE (FILE NAME) + MODE & EXCITATION VOLTAGE
WRITE(FNAME,1040) IMGLBL,MODE
1040 FORMAT(A8,1.',I3)
DO 110 I=1,8
   IF (FNAME(I:I).EQ.' ') FNAME(I:I)='_'
110 CONTINUE
DO 120 I=10,12
   IF (FNAME(I:I).EQ.' ') FNAME(I:I)=10'
120 CONTINUE
FNAME(13:13) = CHAR(0)
WRITE(STRING,1050) FNAME,VOLT
1050 FORMAT(Al2,I3,'V')
STRING(17:17) = CHAR(0)

C WRITE TEXT IN WHITE (255)
CALL SETIND(255)
CALL MOVETO(50, 410)
CALL TEXT(STRING,3)

C LABEL THE IMAGE WITH THE DATE AND FREQUENCY
CALL DATE(DATSTR)
CALL TIME(TIMSTR)
WRITE(STRING,1060) DATSTR,TIMSTR
1060 FORMAT(A8,' 1,15,'Hz')
DO 125 I=1,8
   IF (STRING(I:I).EQ.' ') STRING(I:I)=10'
125 CONTINUE
STRING(17:17) = CHAR(0)
CALL MOVETO(50, 440)
CALL TEXT(STRING,3)

C SAVE THE IMAGE IN THE FILE
IVAL = IWINTO(4096, FNAME, BUFFER)
IF (IVAL.EQ.0) THEN
   PRINT *,/'IWINTO ERROR CODE 0' 
   PRINT *,/'COULD NOT OPEN FILE'
   PRINT *,/'FILE NAME IS:','FNAME'
   STOP
END IF
IF (IVAL.EQ. -1) THEN
   PRINT *,/'IWINTO ERROR CODE -1' 
   PRINT *,/'TRANSFER TERMINATED PREMA TUR ELY' 
   PRINT *,/'(PROBABLY A FULL DISK)' 
   PRINT *,/'FILE NAME IS:','FNAME'
   PRINT *
   PRINT *,'/CHECK THE DISK AND TRY AGAIN'
   STOP
END IF
GOTO 105
C END OF MODE LOOP
150 CONTINUE
PRINT *
WRITE(6,1070)
1070 FORMAT($,' ANOTHER TEST OBJECT? (Y/N) ')
READ (5,'(A)') ROW
IF (ROW.EQ.'Y' .OR. ROW.EQ.'y') GOTO 100
C
CALL PEXIT
STOP
END
C*******************************************************************************/
C
C A DELAY IN TERMS OF "I" VERTICAL RETRACES
C*******************************************************************************/
DO 100 N = 1, I
   CALL VWAIT()
100 CONTINUE
RETURN
END
C*******************************************************************************/
C
C SET UP THE GAINS, ETC. TO GET A GOOD IMAGE TO START WITH
C*******************************************************************************/
CHARACTER ANS*1
INTEGER OSV, GV
C
PRINT *, 'The optimal gain and offset for A/D conversion have'
PRINT *, 'been set. This routine allows you to change them to'
PRINT *, 'get a better image for the actual data. Note that if'
PRINT *, 'the image is clipped here, it cannot be fixed with'
PRINT *, 'post processing.'
PRINT *
PRINT *, 'Adjust offset first, then gain in a separate pass.'
PRINT *
PRINT *, 'PRESS ENTER WHEN SOME IMAGE IS READY'
READ (5,*)
CALL CLEAR(0,7)
CALL SNAP(1)
100 CONTINUE
PRINT *, 'ADJUST: (Offset, Gain, Exit)'
READ (5,'(A)') ANS
IF (ANS.EQ.'O' .OR. ANS.EQ.'o') THEN
   PRINT *, 'Enter OFFSET: 0 (darker) - 255 (lighter)'
   READ (5,*) OSV
   OSV = AMINO(255,AMAXO(0,OSV))
   CALL OFFSET(OSV)
   CALL CLEAR(0,7)
   CALL SNAP(1)
ENDIF
IF (ANS.EQ.'G' .OR. ANS.EQ.'g') THEN
   PRINT *, 'Enter GAIN: 0 (darker) - 255 (lighter)'
   READ (5,*) GV
   GV = AMINO(255,AMAXO(0,GV))
   CALL GAIN(GV)
   CALL CLEAR(0,7)
   CALL SNAP(1)
ENDIF
IF (ANS.NE.'E' .AND. ANS.NE.'e') GOTO 100
RETURN
END
C*******************************************************************************/
C
SUBROUTINE DATE(S)
 CHARACTER S*8
 CALL GETDAT(IYR, IMON, IDAY)
WRITE(S,1000) IMON,IDAY,IYR-1900
1000 FORMAT(12,/'',12,'/',12)
RETURN
END

SUBROUTINE TIME(S)
CHARACTER S * 8
CALL GETTIM(IHR, IMIN, ISEC, 1100TH)
WRITE(S,1000) IHR,IMIN,ISEC
1000 FORMAT(12,':',12,:',12)
RETURN
END

SUBROUTINE UPCASE(S)
CHARACTER S * 8
INTEGER I
DO 100 I=1,8
   IF( ICHAR(S(I:I)).GT.ICHAR('a') .AND.
     > ICHAR(S(I:I)).LT.ICHAR('z') ) THEN
      S(I:I)=CHAR(ICHAR(S(I:I))-ICHAR('a')+ICHAR('A'))
   ENDIF
100 CONTINUE
RETURN
END
program piphist;
( Calculate and display a histogram for an image from the PIP board. 
   Chris Miller 901207

   PIP image is 512x480, and upside down.

   v910701 cjm Now uses BlockRead to speed up input.
   v910812 cjm Tried various color schemes
)
uses
   cjm, Crt, Dos, Drivers, (Graph) HPGL;
const
   version = '910812';
   FracLow = 0.3;
   FracHigh = 0.95;
var
   grDriver : integer;
   grMode : integer;
   errCode : integer;
   iFileName : string;
   iFile : file;
   hist : array[0..255] of word;
   integr : array[0..255] of real;
   maxpixel,
   minpixel : word;
   ImgRows : array[1..2048] of byte; ( four rows a a time )
   result : word;
   c : char;
   i, j : integer;
   ilow, ihigh : integer;
   xbase, ybase : integer;
   r : real;
   s : string;
   col : byte;
   TextH : integer;

procedure Abort(Msg : string);
begin
   Writeln(Msg, ': ', GraphErrorMsg(GraphResult));
   Halt(1);
end;

begin
   if (ParamCount - 1) or (Paramstr(1) = '?') then
   begin
      writeln('Usage: piphist image.fil');
      Halt;
   end;

   iFileName := ParamStr(1);
   if not FileExists(iFileName) then
   begin
      writeln('File ', UpStr(iFileName), ' not found');
      Halt;
   end;
   Assign(iFile,iFileName);
   Reset(iFile,1);

   ( Read in the data, and tabulate for the histogram )
   for i:=0 to 255 do hist[i]:=0;

   write('Processing line ');
   col := WhereX;
   write(' 0 of 480.');
   for i:=1 to 480 div 4 do begin

   end;
if (i mod 10) = 0 then begin
  GotoXY(col, WhereY);
  write(4*i:3);
end;
BlockRead(ifile, ImgRows, SizeOf(ImgRows), result);
for j:=1 to 512 * 4 do
  Inc(hist[ImgRows[j]]);
end;

( find the maximum & minimum pixel bin values )
maxpixel := hist[0];
minpixel := hist[0];
for i:= 1 to 255 do begin
  if hist[i] > maxpixel then maxpixel := hist[i];
  if hist[i] < minpixel then minpixel := hist[i];
end;

( create the integral )
integral[0] := hist[0] / maxpixel;
for i:=1 to 255 do
  integral[i] := integral[i-1] + hist[i]/maxpixel;

( draw the histogram )
grDriver := Detect;
InitGraph(grDriver, grMode, '\tp');
SetColor(White);
s := 'PIPHIST: Histogram plotting for PIP board output    CJM '+version;
( base location for the rectangle )
xbase := 50;
TextH := TextHeight('A');
ybase := 2;
OutTextXY(xbase, ybase, s);
ybase := ybase + 2*TextH;
SetColor(DarkGray);
Rectangle(xbase-3, ybase-2, xbase+255+3, ybase+200+1);
SetColor(red);
SetLineStyle(DottedLn, O, NormWidth);
for i := 0 to 255 do ( draw vertical grid lines every 10 counts )
  if (i mod 10) = 0 then Line(xbase+2*i, ybase, xbase+2*i, ybase+200);

ybase := ybase+200;
SetColor(White);
SetLineStyle(SolidLn, 0, NormWidth);
for i := 0 to 255 do begin
  r := hist[i];
  r := 200*r/maxpixel;
  if (i mod 20)=0 then SetColor(red)
    else SetColor(white);
  Line(xbase+2*i, ybase-trunc(r), xbase+2*i, ybase);
end;
MoveTo(50, 220);
SetColor(blue);
for i := 1 to 255 do begin
  LineTo(xbase+2*i, ybase-trunc(200*integral[i]/integral[255]));
end;

( tag ends of scale )
SetColor(White);
SetLineStyle(SolidLn, 0, NormWidth);
ilow := 0;
Line(xbase+2*ilow, ybase + TextH div 2);
s := '0';
OutTextXY(xbase+2*ilow, TextWidth(s) div 2, ybase + TextH, s);
ilow := 255;
Line(xbase+2*ilow, ybase + TextH div 2);
s := '255';
OutTextXY(xbase+2*ilow, TextWidth(s) div 2, ybase + TextH, s);

( tag recommended processing lines )
ilow := 0;
while (integral[ilow] < FracLow*integral[255]) do Inc(ilow);
SetColor(green);
SetLineStyle(SolidLn,0,ThickWidth);
r := hist[ilow];
r := 200*r/maxpixel;
Line(xbase+2*ilow,ybase-trunc(r), xbase+2*ilow,ybase+TextH);
s := IntToStr(ilow);
OutTextXY(xbase+2*ilow-TextWidth(s) div 2, ybase+2*TextH, s);
ihigh := 254;
while (integral[ihigh] > FracHigh*integral[255]) do Dec(ihigh);
SetColor(green);
r := hist[ihigh];
r := 200*r/maxpixel;
Line(xbase+2*ihigh,ybase-trunc(r), xbase+2*ihigh,ybase+TextH);
s := IntToStr(ihigh);
OutTextXY(xbase+2*ihigh-TextWidth(s) div 2, ybase+2*TextH, s);

( labeling )
SetColor(White);
ybase := ybase +4*TextH;
s := 'Pixel population by value for the file: ' + UpStr(iFileName);
OutTextXY(xbase,ybase, s);
ybase := ybase +2*TextH;
s := 'Minimum pixel (bin) count = ' + IntToStr(minpixel);
OutTextXY(xbase,ybase, s);
ybase := ybase +2*TextH;
s := 'Maximum pixel (bin) count = ' + IntToStr(maxpixel);
OutTextXY(xbase,ybase, s);
ybase := ybase +2*TextH;
s := 'Suggested processing range (for image expansion) is: ' + IntToStr(ilow) + ' - ' + IntToStr(ihigh);
OutTextXY(xbase,ybase, s);

while KeyPressed do c:=ReadKey;
repeat until KeyPressed;
CloseGraph;
End.
APPENDIX D—LISTING OF PC IMAGE DISPLAY PASCAL PROGRAM

($R-,S-)  
($define ega)  
program pipdisp;  
{ process and display an image from the pip board  
  Christopher J. Miller  901209  

  PIP image is 512x480, and upside down.  
  v910701 cjm  Now uses BlockRead to speed up the input.  
  v910725 cjm  In InitGraph, tp path is now \texttt{c:\tp}; OutputHelp procedure.  
  v910812 cjm  Check for \textless Esc\textgreater{} to quit.  
}  
uses  
cjm, Crt, Dos, Drivers, Graph;  
type  
  ColorMapType = array[0..151 of word;  
const  
  version = '910812';  
  RowSize = 512;  
  ColorSeq : ColorMapType  
  =(  
    Black,DarkGray,Blue,Red,Brown,Magenta,Green,Cyan,  
    LightGray,LightBlue,LightRed,LightMagenta,LightGreen,Yellow,  
    LightCyan,White);  
  BWSeq : ColorMapType  
  ==(  
    0,1,4,5,8,6,2,3,9,12,7,10,11,13,14,15);  
var  
grDriver : integer;  
grMode : integer;  
errCode : integer;  
iFileName : string;  
ifile : file;  
ImgRows : array[1..2048] of byte;  
result : word;  
hist : array[0..255] of word;  
integr : array[0..255] of real;  
pl, ph : byte;  
vskip : byte;  
msgl : integer;  
ColorMap : ColorMapType;  
UseColor : (bw,color,user);  
MapFile : text;  
MapName :
  PathStr;  
c : char;  
i, j, k : integer;  
iptr : integer;  
row : integer;  
xoffset : integer;  
r : real;  
s : string;  
w : word;  
col : integer;  
procedure Abort(Msg : string);  
begin  
  Writeln(Msg, ': ', GraphErrorMSg(GraphResult));  
  Halt(1);  
end;  

14
procedure CalcExpansion;
( Calculate the image expansion pixel values from the 30%/95% rule )
const
  FracLow  = 0.3;
  FracHigh = 0.95;
var
  i : integer;
  maxpixel : word;
begin
  writeln('Calculating the auto-scaling');
  Reset(iFile, 1);
  ( Read in the data, and tabulate for the histogram )
  for i:=0 to 255 do hist[i]:=0;
  write('Processing line ');
  col := WhereX;
  write(' of 480.');
  for i:=1 to 480 div 4 do begin
    if (i mod 10) = 0 then begin
      GotoXY(col,WhereY);
      write(4*i:3);
    end;
    BlockRead(iFile,ImgRows,sizeof(ImgRows),result);
    for j:=1 to 512 * 4 do Inc(hist[ImgRows[j]]);
  end;
  maxpixel := hist[0];
  for i := 1 to 255 do
    if (hist[i] > maxpixel) then maxpixel := hist[i];
  ( create the integral )
  integr[0] := hist[0] / maxpixel;
  for i := 1 to 255 do
    integr[i] := integr[i-1] + hist[i]/maxpixel;
  ( calc pl & ph processing values )
  pl := 0;
  while (integr[pl] < FracLow*integr[255]) do Inc(pl);
  ph := 254;
  while (integr[ph] > FracHigh*integr[255]) do Dec(ph);
  writeln;
  writeln('Low value =',pl:4);
  writeln('High value = ',ph:4);
  Pause('');
end;

Procedure OutputHelp;
Begin
  writeln('Where the low (-p) and high (-P) pixel values are used to expand.');
  writeln('If not specified, the values for -p & -P are calculated from the integral ');
  writeln('of pixel bin values: the low end is at 30% of the total.');
  writeln('The skip option is the number of lines at the top of the image');
  writeln('to skip (defaults to ,vskip,'.');
  writeln('The black and white color map is used instead of the color one.');
  writeln('[-m:filename] user defined colormap');
  writeln('[-v] Force VGA mode graphics.');
End;

begin
  ($ifdef ega)
    ( Register the EGAVGA driver )
    if RegisterBGI(driver(EGAVGA driverProc) < 0 then
      Abort('EGA/VGA');
  ($endif)
  pl := 255;
.phi := 0;
.vskip := 80;
.UseColor := color;
.grDriver := Detect;

if ParamCount = 0 then begin
  OutputHelp;
  Halt;
end;

for i:=1 to ParamCount do begin
  if ParamStr(i) = '?' then begin
    OutputHelp;
    Halt;
  end;
  s := ParamStr(i);
  if (s[1] = '-') then
    case s[2] of
      'p' : Val(Copy(s,4,Length(s)-3),pl,imsg);
      'P' : Val(Copy(s,4,Length(s)-3),ph,imsg);
      's' : Val(Copy(s,4,Length(s)-3),vskip,imsg);
      'b' : UseColor := bw;
      'm' : begin
        UseColor := User;
        MapName := Copy(s,4,Length(s));
      end;
      'v' : grDriver := VGA;
    end;
  end;
end;

case UseColor of
  color : ColorMap := ColorSeq;
  bw : ColorMap := BWSeq;
  user : begin
    Assign(MapFile,MapName);
    Reset(MapFile);
    for i := 0 to 15 do
      read(MapFile, ColorMap[i]);
  end;
end;

iFileName := ParamStr(1);
if not FileExists(iFileName) then begin
  writeln('File ',UpStr(iFileName),' not found');
  Halt;
end;
Assign(iFile,iFileName);
Reset(iFile, 1);

if (pl = 255) and (ph = 0) then
  CalcExpansion;

if (pl > ph) then begin
  i := ph;
  ph := pl;
  ph := i;
end;

ph_pl := ph-pl;

{ Display the image while processing }
grDriver := Detect;
InitGraph(grDriver,grMode,'c:\tp');

{ if VGA, set gray scale levels }
if (grDriver=VGA) then begin
  j := Trunc(255.0*MaxColors/i);
  SetRGBPalette(i, j,j,j);
end;
SetColor(White);
xoffset := (GetMaxX - (RowSize-1) ) div 2;

(* ImageSize for a line of 512 pixels is: *)
(* for herc: 70 bytes = 64 + 6 *)
(* for ega: 262 bytes = 256 + 6 *)

Reset(iFile, 1);  
( skip some of the lines at the top )
if (vskip > 8) then
  for j := 1 to (vskip div 4) do
    BlockRead(iFile, ImgRows, SizeOf(ImgRows), result);

BlockRead(iFile, ImgRows, SizeOf(ImgRows), result);
j := 0;
while (result = 2048) and (j < GetMaxY) do begin
  iptr := 0;
  for row := 0 to 3 do begin
    for i-=0 to RowSize-1 do begin
      Inc(iptr);
      k := integer(ImgRows[iptr]) -pt;
      if (k < 0) then
        w := 0
      else if (k > ph-pl) then
        w := 255
      else
        w := ((k shl 8) -1) div ph_pl;
      (Now scale 0..255 to 0..15 for color selection)
      w := w shr 4;
      PutPixel(xoffset+i,j,ColorMap[w]);
    end;
    Inc(j);
  end;
  BlockRead(iFile, ImgRows, SizeOf(ImgRows), result);
end;

( Add colored pixel map key )
SetColor(white);
Rectangle(0,301,11,44);
for j := 0 to 255 do begin
  k := j -pt;
  if (k < 0) then w := 0
  else w := (256*k-1) div ph_pl;
  if (w > 255) then w := 255
  w:=w shr 4;
  SetColor(ColorMap[w]);
  Line(1,300-j, 10,300-j);
  if (ColorMap[w] = black) then SetColor(white);
  if (j mod 16)=0 then OutTextXY(20,300-j-2,IntToStr(j));
end;

while KeyPressed do c:=ReadKey;
repeat until KeyPressed;
CloseGraph;
End.
REFERENCES


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**Table I.** Natural frequencies for CMID forward blades.

**Table II.** Natural frequencies for CMID aft blades.

1. Predicted frequencies.
2. Remeasured after tunnel test.
### TABLE III.—NATURAL FREQUENCIES FOR CM2D FORWARD BLADES

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\[
\bar{f} = 954, \quad \sigma = 10, \quad 22, \quad 19
\]

**Pred**² 980, 1971, 2656, 3615

1 Blade used in fatigue testing.
2 Predicted frequencies.

### TABLE IV.—NATURAL FREQUENCIES FOR CM2D AFT BLADES

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\[
\bar{f} = 954, \quad \sigma = 8, \quad 20, \quad 42, \quad 33
\]

**Pred**³ 962, 2038, 2592, 3316

1 Image marked as #114.
2 Image marked as #214.
3 Predicted frequencies.
### TABLE V.—CM1 D BLADE SETS

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### TABLE VI.—CM2 D BLADE SETS

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### TABLE VII.—REPRESENTATIVE COMPRESSION RESULTS

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Figure 1 – CM1D: Low Tip Speed Propfan Fore and Aft Designs

Figure 2 – CM2D: High Tip Speed Propfan Fore and Aft Designs
Figure 3 – Holography Setup for Computer Based Image Capture
Figure 4 — CM1DF first bending mode

Figure 5 — CM1DF second bending mode

Figure 6 — CM1DF first torsion mode

Figure 7 — CM1DF second torsion mode
Figure 8 — CM1DA first bending mode

Figure 9 — CM1DA second bending mode

Figure 10 — CM1DA first torsion mode

Figure 11 — CM1DA second torsion mode
Figure 12 — CM2DF first bending mode

Figure 13 — CM2DF second bending mode

Figure 14 — CM2DF first torsion mode

Figure 15 — CM2DF second torsion mode
Figure 16 – CM2DA first bending mode

Figure 17 – CM2DA second bending mode

Figure 18 – CM2DA first torsion mode

Figure 19 – CM2DA second torsion mode
Solid symbols denote fatigued blade data.
Figure 24 – CM1DF022 Four Hologram (1B,2B,1T,2T) Composite Image
Figure 25 - CM1DA025 Four Hologram (1B,2B,1T,2T) Composite Image
Figure 26 – CM2DF010 Four Hologram (1B,1T,2B,2T) Composite Image
Figure 27 – CM2DA008 Four Hologram (1B,1T,2B,2T) Composite Image
Figure 28 – Fatigued CM1DF022 Four Hologram Composite Image
Figure 29 – Fatigued CM11DA025 Four Hologram Composite Image
Figure 30 — Representative Photographic Hologram

Pixel value histogram for the file: CM1DA001.2
Minimum pixel (bin) count = 0
Maximum pixel (bin) count = 5641
Suggested processing limits (for image expansion) are: 63 - 117

Figure 31 — PC Histogram display showing recommended image enhancement limits
Figure 32 – PC Histogram display showing recommended image enhancement limits

Figure 33 – PC Histogram display showing recommended image enhancement limits
Figure 34 – Composite: static image and holograms of first 8 modes
Figure 35 – Single mode hologram (uncompressed) printed in 16 gray levels
Figure 36 – Single mode hologram, JPEG compressed with Q=20, printed in 16 gray levels
Holographic Testing of Composite Propfans for a Cruise Missile Wind Tunnel Model

Christopher J. Miller

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

Responsible person, Christopher J. Miller, (216) 433–6179.

Unclassified - Unlimited
Subject Category 07

Each of the approximately 90 composite propfan blades constructed for a 55 percent scale cruise missile wind tunnel model were holographically tested to obtain natural frequencies and mode shapes. These data were used not only for quality assurance, but also to select sets of similar blades for each blade row. Presented along with the natural frequency data is a description of a computer-based image processing system developed to supplement the photographic-based system for holographic image analysis and storage. The new system is quicker and cheaper, the holograms are indexed better, and several engineers can access the data simultaneously. The only negative effect is a slight reduction in image resolution, which does not influence the end use.