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NORMAL MODE ANALYSIS OF A ROTATING GROUP OF LASHED TURBINE BLADES BY SUBSTRUCTURES

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SUMMARY

A group of 5 lashed identical steam turbine blades is studied through the use of single level substructuring using NASTRAN Level 15.1. An altered version, similar to DMAP Program Number 3 of the NASTRAN Newsletter, of Rigid Format 13.0 was used. Steady-state displacements and stresses due to centrifugal loads are obtained both without and with consideration of differential stiffness. The normal mode calculations were performed for blades at rest and at operating speed. Substructuring lowered the computation costs of the analysis by a factor of four.

INTRODUCTION

Triangular plate elements have been used by Westinghouse and others (see Ref. 1) in NASTRAN to analyze rotating turbine blades.

There was a need to analyze a group of five lashed 0.79-m (31-inch) steam turbine blades for operation at 60 revolutions per second. Steady-state displacements and stresses were needed as well as the natural frequencies, mode shapes, and stress patterns.

Based on NASTRAN calculations on a single 0.79-m blade with associated lashing wires, it was decided that a finite element mesh of 700 CTRIA2 elements and 407 grid points would be used to represent each turbine blade. The root flexibility was approximated by 11 CELAS2 elements.

It was discovered that approximately two hundred degrees of freedom would be required in the a-set for each blade using Guyan reduction, if accurate stress results were to be found for the modes to be evaluated. Whether or not Guyan reduction was to be used and whether the inverse power or Givens method were used for the eigenvalue extraction, it was apparent that calculation costs would have been prohibitive if substructuring were not used.

This paper describes the successful substructuring analysis of the group of blades. The steady-state stresses were obtained for operation at 60 revolutions per second and the natural frequencies were obtained for the first nine modes at both 0 revolutions per second and at 60 revolutions per second.

METHOD OF ANALYSIS

The finite element mesh used to represent a turbine blade or substructure is shown in Fig. 1. The middle sections of the lashing wires and airfoil are sl Each lashing wire actually resembles a variable thickness plate more than a wire The auxiliary program which produces these plots views normal to the middle surface of the lashing wire. The airfoil is highly twisted, and near the base it is highly curved. No one viewing angle could provide a clear representation of element layout. Thus the auxiliary program which produces the element geometry and isostress plots opens up each cross section. Different scales are used for the lashing wires than for the airfoil in figure 1.

Each blade or substructure has 407 grid points. The 2442 degrees of freedom associated with these points are reduced through single point constraint and omits to an a-set of 301 degrees of freedom. One hundred twenty of these degrees of freedom are at the tips of the lashing wires and are required for connecting adjacent blades or substructures. Sixty degrees of freedom are common between adjacent blades.

The combined matrices for the group of five blades then has 1505 less four times sixty or 1265 degrees of freedom. Single point constraints to remove rotations about the normals to the surface of the exterior lashing wires reduce the system of equations to be solved to 1245. The half-bandwidth is 301 with no active columns. No secondary Guyan reduction was performed to reduce the number of degrees of freedom as the resulting bandwidth would have to be significantly larger than 301 for accurate results. The inverse power method with shifts was used to solve the eigenvalue problems.

The identical substructure concept as described in Sec. 1.10.5 of reference 2 was used. Five phases were required as shown in figure 2. In some cases it was deemed advisable to use more than the one user tape shown between phases. Even though the differential stiffness would be somewhat different for each of the five substructures, only one (the center blade) was generated in Phase III and used in Phase IV. This approach reduced the total calculation costs by about 20%. The inaccuracies of this approximation were felt to be about the same as those due to some of the other approximations made. Runs IV and V were split into several parts to enable shorter individual runs.

The mesh for the airfoil was generated by a preprocessor computer program. The meshes for the platform and the two lashing wires were generated by hand. The isostress lines for the centrifugal loading and for the scaled eigenvectors for the airfoil and lashing wires were plotted with a postprocessor computer program which reads images of punched element stress cards. A

STRESS(PRINT,PUNCH) = ALL

card was placed in the Case Control Deck. However, job control cards were used to store the card images on two disks and to prevent the punching of cards. Over two hundred thousand card images were produced in the Phase V runs. An intermediate program was written to enable the isostress plotting program to handle the stress information on the disk more efficiently.

Table 1 shows the calculation times for the substructuring analysis for each phase. The mesh was generated on a CDC 6600 computer and the other runs were made on an IBM 370-165 computer.

Table 2 shows the projected calculation times for the analysis of five blades without substructuring provided enough disk space were available which is extremely doubtful. In addition, checkpointing and restarting would be essential due to the extremely long total running times. However, Level 15.1 NASTRAN requires that this be done on a single physical tape which obviously would not hold enough information. The user would be required to use DMAP statements to transfer data from one run to another on user tapes rather than checkpoint tapes. Even then, some matrices might be too large to fit on a single tape.

When costs of the CALCOMP plotter are added to the computer costs shown, the total cost for a nonsubstructuring analysis, if possible, would have been about four times the total cost of the substructuring analysis performed in this study.

The arrangement of the NASTRAN decks including the Executive Control Decks are shown in the appendix.

RESULTS AND DISCUSSION

The natural frequencies, mode shapes, and stresses for the first nine modes of a group of five lashed rotating steam turbine blades were found. The natural frequencies, in general, agreed well with experimental values.

A Campbell Diagram was prepared to determine possible resonances during various operating conditions.

The pseudo steady-state deformations and stresses due to the centrifugal forces at operating speed were found. This enables the calculations of the fluid flow through the row of blades through the passages that actually occur in operation and not through the passages in the undeformed condition. Thus, NASTRAN provides the designer of flexible turbine blades with a tool to help obtain near optimal fluid flow characteristics between the airfoils.

A sample isostress plot for one of the surfaces for one of the blades for one of the modes is shown in figure [illegible].

RECOMMENDATIONS

1. NASTRAN Level 15 with its substructuring capability can and should be used for many structural problems.

2. When preparing data for large problems, a mesh generator computer program should be used as much as possible.

3. For very rigid rotating turbine blades or blade groups, Rigid Formats 1 and 3 will give accurate results and should be used. For more flexible blades, Rigid Formats 4 and 13, which include the differential stiffness matrix should be used. For even more flexible blades, it may be necessary to ALTER the centripetal acceleration matrix (see Ref. 3) into Rigid Formats 4 and 13.

4. In order to encourage more users to use the substructure capability of NASTRAN and in order to reduce the effort of the user in creating and checking DMAP packages and substructuring data, it is urged that substructuring be made more automatic (see Ref. 4).

5. Rigid Format 13 should be documented in the NASTRAN documentation.

ACKNOWLEDGEMENTS

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CONCLUSIONS

1. The determination of the natural frequencies, mode shapes and states of stress for lashed rotating and non-rotating steam turbine blades is feasible using the general purpose computer program NASTRAN.

2. Substructuring can greatly reduce the computer costs of large problems. For the analysis performed here, the total computer expenses including mesh generation and stress plotting were one-fourth what they would have been without substructuring. The NASTRAN runs cost one-sixth as much using substructuring than they would have cost without substructuring.

3. Choice of the proper root flexibility is important to produce accurate frequencies and stresses for all modes.

4. Mode shapes and isostress lines for the fifth through ninth modes varied significantly between those found at 0 revolutions per second and those found at 60 revolutions per second. This variation is due both to the flexibility of the blade group and to the coupling between modes as the frequencies are close together. The mode shape of the fifth mode at zero revolutions per

second is similar to the mode shape of the sixth mode at 60 revolutions per second.

REFERENCES

1. Van Nimwegen, R. R., and Tepper, S.: High Pressure Turbine Blade Stress Analysis. NASTRAN: Users' Experiences. NASA TM X-2637, 1972, pp. 477-484.

2. McCormick, C. W., ed.: The NASTRAN User's Manual. NASA SP-222(01), 1972.

3. Patel, J. S., and Seltzer, S. M.: Complex Eigenvalue Analysis of Rotating Structures. NASTRAN: Users' Experiences. NASA TM X-2637, 1972, pp. 197-234.

4. Hennrich, C. W., and Konrath, E. J., Jr.: Substructure Analysis Techniques and Automation. NASTRAN: Users' Experiences. NASA TM X-2893, 1973, pp. 323-393. (Paper no. 17 of this compilation.)

APPENDIX

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NASTRAN SUBSTRUCTURE ANALYSIS
DIFFERENTIAL STIFFNESS MODAL AND STATIC SOLUTION
IDENTICAL SUBSTRUCTURES
LISTING OF ---PHASE 1---
   (INITIAL SUBSTRUCTURE ANALYSIS)


ID DIFFMOD,PHASE1
DIAG 2,8,13,14
APP DISP
TIME 25
SOL 13,0
CHKPNT YES
ALTER 40,40
SMA3 GEI,KGGX/KGG/V,N,LUSET/V,N,NOGENL/V,N,NOSIMP$
ALTER 76
JUMP LBLX$
ALTER 78
LABEL LBLX$
ALTER 86
FBS LOO,UOO,PO/UOOV$
CHKPNT UOOV$
OUTPUT1 KAA,PL,PARVECT1,PARVECT2,PARVECT3//C,N,-1/C,N,0$
OUTPUT1 PARVECT4,PARVECT5,,,//C,N,0/C,N,0$
ALTER 87 145
ALTER 151 152
ENDALTER
CEND
   (CASE CONTROL DECK)
BEGIN BULK
   (INCLUDE ALL NECESSARY STR  TURAL DATA PLUS THE SUBSTRUCTURING
    MATRIX OPERATORS   )
ENDDATA
END* $ INCLUDE THIS CARD FOR IBM 360/370

  ---COMMENTS---
     DISP APPROACH.
     ALL ANALYSIS SET DEGREES OF FREEDOM SHOULD BE INCLUDED ON ASET CARDS.
     PARTITIONING VECTORS WHICH PROVIDE THE INFORMATION OF HOW THESE
     SUBSTRUCTURES ARE TIED TOGETHER, MUST BE INCLUDED IN BULK DATA CARDS.
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```

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NASTRAN SUBSTRUCTURE ANALYSIS
DIFFERENTIAL STIFFNESS MODAL AND STATIC SOLUTION
IDENTICAL SUBSTRUCTURES
LISTING OF ---PHASE II---
   (STATIC SUBSTRUCTURE COUPLING ANALYSIS)


ID DIFDYNM,PHASE2
TIME 30
APP DMAP
DIAG 2,9,13,14
BEGIN$
PARAM //C,N,NOP/V,N,TRUE=-1$
INPUTT1 /KAA,PL,,,/C,N,-3/C,N,1$    INP1
FILE KAA=SAVE/PL=SAVE$
LABEL LOOP99$
INPUTT1 /E,,,,/C,N,0/C,N,1$
MERGE, ,,,KAA,E,/KGGT$
ADD KGG,KGGT/KT$
EQUIV KT,KGG/TRUE$
MERGE, ,PL,,,,E/PGT/C,N,+1$
ADD PG,PGT/PT$
EQUIV PT,PG/TRUE$
REPT LOOP99,4$
PARTN KGG,SPCV,/KRED,,,/C,N,-1$
PARTN PG,,SPCV/PRED,,,/C,N,1$
SOLVE KRED,PRED/ULVT/C,N,1$
MATPRN ULVT,,,,//$
MERGE, ULVT,,,,,SPCV/ULVTT/C,N,1$
MATPRN ULVTT,,,,//$
$   WRITE USER'S TAPE FOR PHASE 3 DATA RECOVERY.
INPUTT1 /,,,,/C,N,-3/C,N,1$    INP1
INPUTT1 /,,,,/C,N,2/C,N,1$     INP1
OUTPUT1, ,,,,//C,N,-1$
LABEL LOOP98$
INPUTT1 /Q,,,,/C,N,0/C,N,1$
MATPRN Q,,,,//$
PARTN ULVTT,,Q/,ULV,,/C,N,1$
MATPRN ULV,,,,//$
OUTPUT1 Q,ULV,,,//$INPT
REPT LOOP99,4$
OUTPUT1, ,,,,//C,N,-3$
END$
CEND
    (CASE CONTROL DECK)
BEGIN BULK
     INCLUDE MATRIX OPERATORS
ENDDATA
END$ $ INCLUDE THIS CARD FOR IBM 360/370

  ---COMMENTS---
     DMAP APPROACH.
     REPEATING LOOPS.
     ADDITIONAL SINGLE POINT CONSTRAINTS ARE APPLIED VIA MATRIX PARTITION.
     PARTITIONING VECTOR SPCV MUST BE INCLUDED IN BULK DATA DECK.
     THE BULK DATA DECK MUST INCLUDE THE DMI CARDS FOR THE INITIALI-
     ZATION OF KGG AND PG.
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```

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NASTRAN SUBSTRUCTURE ANALYSIS
DIFFERENTIAL STIFFNESS MODAL AND STATIC SOLUTION
IDENTICAL SUBSTRUCTURES
LISTING OF ---PHASE III---
   (STATIC DATA RECOVERY AND INITIAL DIFFERENTIAL STIFFNESS)


ID DIFFDYN,PHASE3
DIAG 2,8,13,14
APP DISP
SOL 13,0
CHKPNT YES
TIME 70
ALTER 3,7
ALTER 19,93
INPUTT1 /,,,,/C,N,-1$
OUTPUT1, ,,,,//C,N,-1/C,N,1$
PARAM //C,N,NOP/V,N,MARK=2$
SAVE MARK$
PARAM //C,N,NOP/V,N,BLADE=0 $
JUMP LOOP99$
LABEL LOOP99$
PARAM //C,N,ADD/V,N,BLADE/V,N,BLADE/C,N,1$
PRTPARM //C,N,0/C,N,BLADE $
INPUTT1 /E,UIV,,,/C,N,0$
ALTER     103
FILE KBLL=SAVE/MAA=SAVE/PBL=SAVE$
PARAM //C,N,SUB/V,N,MARK/V,N,MARK/C,N,1$
PRTPARM //C,N,0/C,N,MARK$
COND DIFF3,MARK$
JUMP SKIPDF$
LABEL    DIFF3$
PARAM //C,N,ADD/V,N,MARK/V,N,MARK/C,N,100$
ALTER      104
SAVE       DSCOSET$
ALTER 105,105
ALTER 106,107
EQUIV     KDGG,KDNN/MPCF2/MGG,MNN/MPCF2$
ALTER 108,108
ALTER        110,110
MCE2       USET,GM,KDGG,MGG,,/KDNN,MNN,,$
ALTER 114,114
ALTER        116,116
SCE1       USET,KDNN,MNN,,/KDFF,KDFS,KDSS,MFF,,$
ALTER 117,117
```

```
CHKPNT KDFS  $
ALTER 120,120
ALTER 124,124
ALTER       125
EQUIV       PL,PBL/DSCOSET/PS,PBS/DSCOSET/YS,YBS/DSCOSET/UOOV,UBOOV/
            DSCOSET$
CHKPNT       PBL,PBS,YBS,UBOOV$
PARAM //C,N,MPY/V,N,NDSKIP/C,N,0/C,N,0$
DSMG2 MPT,KAA,KDAA,KFS,KDFS,KSS,KDSS,PL,PS,YS,UOOV/KBLL,KBFS,KBSS,
      PBL,PBS,YBS,UBOOV/V,N,NDSKIP/V,N,REPEATD/V,N,DSCOSET$
SAVE  NDSKIP,REPEATD $
CHKPNT KBLL,KBFS,KBSS,PBL,PBS,YBS,UBOOV $
LABEL SKIPDF$
OUTPUT1 E,,,,//C,N,0/C,N,1$
REPT LOOP99,4  $
OUTPUT1 KBLL,MAA,PPL,,//C,N,0/C,N,1$
JUMP FINIS$
ENDALTER
$
$  CHECKPOINT DICTIONARY ENTER HERE
$
CEND
    (CASE CONTROL DECK)
BEGIN BULK
ENDDATA
END* $ INCLUDE THIS CARD FOR IBM 360/370
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```
  ---COMMENTS---
     APPROACH DISP.
     RESTART.
     REPEATING LOOPS.
     THE DIFFERENTIAL STIFFNESS MATRICES MAY BE CONSIDERD AS IDENTICAL
     FOR ALL SUBSTRUCTURES PROVIDED THAT THE BOUNDARY EFFECTS ARE NOT LARGE.
     FOR SAVING COMPUTING TIME, THE CENTER BLADE DIFFERENTIAL STIFFNESS
     MATRIX IS CHOSEN TO REPRESENT ALL.
     FOR GENERATING THE A-SET DIFFERENTIAL STIFFNESS MATRIX, THE USER
     MAY EITHER CHOOSE TO USE MODULE SMP1 OR SMP2, THE LATER IS USED IN
     THIS ANALYSIS.
     SOME DATA SETS IN CHKPNT STATEMENTS ARE SELECTIVELY DELETED, FOR
     NASTRAN DOES NOT ALLOW MULTI-REEL CHECK-POINT TAPE, HENCE CANNOT
     ACCOMMODATE ALL THE LARGE SIZE DATA SETS.  PROGRAM INTERRUPTION
     WOULD OCCUR IF THE CHECK-POINT TAPE HAD REACHED TO AN END.
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NASTRAN SUBSTRUCTURE ANALYSIS
DIFFERENTIAL STIFFNESS MODAL AND STATIC SOLUTION
IDENTICAL SUBSTRUCTURES
LISTING OF ---PHASE IV---
   (DIFFERENTIAL STIFFNESS STATIC AND DYNAMIC COUPLING ANALYSIS)


ID DIFFDYN,PHASE4
DIAG 2,8,13,14,16
APP DISP
TIME 100
SOL 13,0
ALTER 1
PARAM //C,N,NOP/V,N,TRUE=-1 $
$ TRUE USED AS PARAMETER IN EQUIV STATEMENTS TO EQUIVALENCE DATA BLOCKS
$
$ DMAP ALTER.  SOL 13,0   PHASE IV.
$ REPEATING LOOP.
$ OMIT, SPC, MPC AND SUPPORT CARDS ARE PERMITTED HERE
$
$ USER MUST USE SPOINT CARD TO ENABLE USE OF SPC AND MPC CARDS
$ USER MUST CREATE NULL SQUARE KT AND MT MATRICES WITH DMI CARDS IN
$      THE BULK DATA DECK
$
ALTER 6,41
ALTER 48,50
ALTER 54,110 $ SKIP STATIC SOLUTION AND FORMULATION OF DIFFERENTIAL
$      STIFFNESS MATRIX
INPUTT1 /,,,,/C,N,-3$
INPUTT1 /KDBB,MBB,PBL,,/C,N,+5/C,N,0$    SKIP 5 BLOCKS AND READ INPT.
FILE KDBB=SAVE/MBB=SAVE/PBL=SAVE$
INPUTT1 /,,,,/C,N,-3$        REWIND INPT.
JUMP LOOP99 $
LABEL LOOP99$ READ AND COMBINE PARTITION, STIFFNESS AND MASS MATRICES
INPUTT1 /E,,,,/C,N,0$      READ PARTITIONING VECTORS FROM INPT.
MERGE, ,,,KDBB,E,/KDAAT1$
ADD KT,KDAAT1/KTT$
EQUIV KTT,KT/TRUE$
MERGE, ,,,MBB,E,/MAAT1$
ADD MT,MAAT1/MTT$
EQUIV MTT,MT/TRUE$
MERGE, ,PBL,,,,E/PBT/C,N,+1$
ADD PB,PBT/PT$
EQUIV PT,PB/TRUE$
REPT LOOP99,4$ TOTAL MATRICES NOW FORMED
EQUIV KT,KDNN/MPCF2 / MT,MNN/MPCF2 $
COND LBL2D,MPCF2 $
MCE1 USET,RG/GM$
MCE2 USET,GM,KT,MT,,/KDNN,MNN,,$
ALTER 116,116
SCE1 USET,KDNN,MNN,,/KDFF,KDFS,KDSS,MFF,,$
ALTER 122,122
SMP1 USET,KDFF,,,/GO,KDAA,NULL1,NULL2,NULL3,,,,,$
ALTER 125
RBMG2 KDAA/LLL,ULL $
CHKPNT LLL ULL $
EQUIV PB,PLB/NOSET $
CHKPNT PLB $
COND PHA4L1,NOSET $
SSG2 USET,GM,YS,KDFS,GO,,PB/,POB,PSB,PLB$
CHKPNT POB,PSB,PLB $
LABEL PHA4L1 $
SSG3 LLL,ULL,KDAA,PLB,NULL2,NULL3,NULL1,POB/UBLV,UBOOV,RBULV,RBU V/V,N,
       OMIT/V,Y,IRES=-1/C,N,1/V,N,EPSI $
```

```
SAVE EPSI $
CHKPNT UBLV,UODV,RULV,RUOV $
COND PHA4L2,IFES $
MATGPR GPL,USET,SIL,RBULV//C,N,L $
MATGPR GPL,USET,SIL,RBUOV//C,N,O $
LABEL  PHA4L2 $
SDR1  USET,PR,UBLV,UBODV,YS,GO,GM,PSB,KOFS,KOSS,/UBGV,PBGG,QBG/C,N,1/C,
      N,BKLO $
MATPRN UBGV,,,,//$
PURGE PBGG,QBG/TRUE $
PARAM //C,N,NOP/V,N,SUP=0 $
INPUTT1 /,,,,/C,N,-3 $
OUTPUT1, ,,,,//C,N,-1/C,N,2 $ INP2
JUMP LOOP97 $
LABEL LOOP97 $
PARAM //C,N,ADD/V,N,SUB/V,N,SUP/C,N,1 $
PRTPARM //C,N,0/C,N,SUP $
INPUTT1 /XX,,,,/C,N,0 $
PARTN UBGV,,XX/,UPV,,/C,N,1 $
MATPRN UBV,,,,//$
OUTPUT1 XX,UBV,,,//C,N,0/C,N,2 $ INP2
REPT LOOP97,4 $
OUTPUT1, ,,,,//C,N,-3/C,N,2 $     INP2
ALTER 138,145
MATPRN PHIG,,,,//$
OUTPUT1, ,,,,//C,N,-1/C,N,1$INP1
INPUTT1 /,,,,/C,N,-3$
OUTPUT1 LAMA,,,,//C,N,0/C,N,1$
PARAM //C,N,NOP/V,N,BLADE=0 $
JUMP LOOP98 $
LABEL LOOP98$ PREPARE AND PLACE PARTITIONED EIGENVECTORS ON TAPE
PARAM //C,N,ADD/V,N,BLADE/V,N,BLADE/C,N,1$
PRTPARM //C,N,0/C,N,BLADE $
INPUTT1 /Q,,,,/C,N,0 $
MATPRN Q,,,,//$
PARTN PHIG,,Q/,PHI,,/C,N,1$
MATPRN PHI,,,,//$
OUTPUT1 PHI,,,,//C,N,0/C,N,1$
REPT LOOP98,4 $
OUTPUT1,,,,, //C,N,-3/C,N,1 $
ENDALTER
CEND
    (CASE CONTROL DECK)
BEGIN BULK
      INCLUDE MATRIX OPERATORS
      INCLUDE PSEUDOSTRUCTURE DATA
ENDDATA
END= $ INCLUDE THIS CARD FOR IBM 360/370

   ---COMMENTS---
      APPROACH DISP.
      REPEATING LOOPS.
      SIMILAR TO PHASE II, BUT USE ALTER OF RIGID FORMAT 13 IN ORDER TO
      EASE THE IMPLEMENTATION OF APPLYING SECOND ORDER OMIT AND CONSTRAINTS
      FOR EIGEN-VALUE EXTRACTION.
      NO SECOND ORDER OMIT IS APPLIED IN THE PRESENT ANALYSIS.
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NASTRAN SUBSTRUCTURE ANALYSIS
DIFFERENTIAL STIFFNESS MODAL AND STATIC SOLUTION
IDENTICAL SUBSTRUCTURES
LISTING OF ---PHASE V---
   (DATA RECOVERY)


ID PHASE,FIVE$    MODAL DIFFERENTIAL
TIME 25
APP DISP
DIAG 2,8,13,14
SOL 13,0
ALTER 30,135
PARAM   //C,N,NOP/V,N,TRUE=-1   $
INPUTT1 /,,,,/C,N,-3/C,N,1 $
JUMP LOOP98 $
LABEL LOOP98 $
ADD       INDICA,PLUS1000/TEMP   $
EQUIV  TEMP,INDICA/TRUE   $
MATPRN  INDICA,,,,//    $
OUTPUT3 INDICA,,,,//C,N,1/C,Y,N1=MAD $
INPUTT1 /UBV,,,,/C,N,1/C,N,1 $
FILE UBOOV=SAVE/YBS=SAVE/GO=SAVE/GM=SAVE/GM=SAVE/PBS=SAVE/KBFS=SAVE/
     KBSS=SAVE$
SDR1 USET,,UBV,UBOOV,YBS,GO,GM,PBS,KBFS,KBSS,/UBGV,,
     QBG/V,N,NOSKIP/C,N,DS1 $
CHKPNT UBGV,QBG $
SDR2 CASECC,CSTM,MPT,DIT,EQEXIN,SIL,GPTT,EDT,BGPDT,,
     QBG,UBGV,EST,/,OQBG1,OUBGV1,OESB1,OEFB1,PUBGV1/C,N,DS1 $
OFP OQBG1,OUBGV1,OESB1,OEFB1,,//V,N,CARDNO $
REPT LOOP98,4 $
INPUTT1 /LAMA,,,,/C,N,-3$
JUMP LOOP99$
LABEL LOOP99$
ADD       INDICA,PLUS1000/TEMP1    $
EQUIV     TEMP1,INDICA/TRUE      $
MATPRN  INDICA,,,,//    $
OUTPUT3  INDICA,,,,//C,N,1/C,Y,N1=MAD    $
INPUTT1 /PHIA,,,,/C,N,0$
ALTER 145
REPT LOOP99,4$
ENDALTER
$
$  CHECKPOINT DICTIONARY ENTER HERE
$
CEND
   (CASE CONTROL DECK)
BEGIN BULK
ENDDATA
END* $ INCLUDE THIS CARD FOR IBM 360/370

  ---COMMENTS---
     APPROACH DISP.
     REPEATING LOOPS.
     THIS RUN GENERATES A HUGE AMOUNT OF STRESS OUTPUT, A OUTPUT3 HAS
     TO BE USED TO MARK THE STRESS FILE, OTHERWISE IT WOULD NOT BE EASY
     TO PLOT IT ON A CALCOMP PLOTTER.
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NASTRAN SUBSTRUCTURE ANALYSIS
DYNAMIC SOLUTION WITHOUT DIFFERENTIAL STIFFNESS
DMAP PROGRAM TO COMBINE TAPES
INPUT TAPE INPT CONTAINS STIFFNESS, LOAD AND PARTITION MATRICES
     (PHASE I OUTPUT)
INPUT TAPE INP1 CONTAINS MASS MATRIX
     (PHASE III OUTPUT)
OUTPUT TAPE INP2
```

```
ID TAPES,TWOONE $
TIME 2
APP DMAP
DIAG 2,8,13,14
BEGIN $
INPUTT1 /KAA,PL,E1,E2,E3/C,N,-3$
INPUTT1 /E4,E5,,,/C,N,0$
INPUTT1 /,,,,/C,N,-3/C,N,1$
INPUTT1 /MAA,,,,/C,N,+6/C,N,1$
OUTPUT1, ,,,,//C,N,-1/C,N,2$
OUTPUT1 KAA,MAA,E1,E2,E3//C,N,0/C,N,2$
OUTPUT1 E4,E5,,,//C,N,0/C,N,2$
OUTPUT1, ,,,,//C,N,-3/C,N,2$
INPUTT1 /,,,,/C,N,-3$
END $
CEND
```

```
ID BSVIRB,PHASE2
TIME 95
APP DISP
DIAG 1,2,8,13,14,16
SOL 3,0
ALTER 1
$
$    DMAP ALTER,  SOL 3,0   PHASE II.
$    REPEATING LOOP.
$    OMIT, SPC, MPC AND SUPPORT CARDS ARE PERMITTED HERE.
$
PARAM //C,N,NOP/V,N,TRUE#-1$
$ TRUE USED AS PARAMETER IN EQUIV STATEMENTS TO EQUIVALENCE DATA BLOCKS
PARAM //C,N,NOP/V,Y,ISTFSEE#-1 $
$ ISTFSEE CONTROLS WHETHER PICTORIAL MATRIX PRINTER USED FOR STIFFNESS
$      TO SEE USE      PARAM    ISTFSEE 1      CARD IN BULK DATA DECK
$ MUST BE VARIABLE AS USED IN COND STATEMENT
PARAM //C,N,NOP/V,Y,MASSSEE#-1 $
$ MASSSEE CONTROLS WHETHER PICTORIAL MATRIX PRINTER USED FOR MASS
$      TO SEE USE      PARAM    MASSSEE 1      CARD IN BULK DATA DECK
$ MUST BE A VARIABLE AS USED IN COND STATEMENT
ALTER 6,41
INPUTT1 /KAA1,MAA1,,,/C,N,-3/C,N,1 $ INP1 -- TWO TAPES
$ INPUTT1 /Z,KAA1,MAA1,,/C,N,-3/C,N,1 $ INP1 -- SIX TAPES
FILE KAA1#SAVE/MAA1#SAVE$
COND SMSEE1,ISTFSEE $
SEEMAT KAA1,,,,// $ PRINTS LOCATION OF NON-ZERO TERMS OF KAA1 MATRIX
LABEL SMSEE1 $
```

```
COND MMSEE1,MASSSEE $
SEEMAT MAA1,,,,//$ PRINTS LOCATION OF NON-ZERO TERMS OF MAA1 MATRIX
LABEL MMSEE1 $
$ PARAM //C,N,NOP/V,N,IPT=0 $ SIX TAPES
LABEL LOOP99$
$ BEGIN LOOP 99
$ PARAM //C,N,ADD/V,N,IPT/V,N,IPT/C,N,1 $ SIX TAPES
$ PRTPARM //C,N,0/C,N,IPT $ SIX TAPES
$ INPUTT1 / E,,,,/C,N,-3/V,N,IPT $ SIX TAPES
INPUTT1 /E,,,,/C,N,0/C,N,1 $ INP1  --  TWO TAPES
MATPRN E,,,,//$
MERGE, ,,,KAA1,E,/KGGT$
ADD KGG,KGGT/KT$
$ KT AND MT ARE CONSIDERED AS SCRATCH DATA BLOCKS AND MUST NOT BE
$      REFERENCED OUTSIDE OF LOOP99
EQUIV KT,KGG/TRUE$
MERGE, ,,,MAA1,E,/MGGT$
ADD MGG,MGGT/MT$
EQUIV MT,MGG/TRUE$
COND SMSEE2,ISTFSEE $
SEEMAT KGG,,,,// $ PRINTS LOCATION OF NON-ZERO TERMS OF KGG MATRIX
LABEL SMSEE2 $
COND MMSEE2,MASSSEE $
SEEMAT MGG,,,,// $ PRINTS LOCATION OF NON-ZERO TERMS OF MGG MATRIX
LABEL MMSEE2 $
REPT LOOP99,4$
$ THE 4 IN REPT LOOP99,4$ INDICATES THAT LOOP99 IS GONE THROUGH 5 TIMES
$      TO CHANGE NUMBER OF IDENTICAL SUBSTRUCTURES ANALYZED FROM 5,
$      CHANGE THIS NUMBER TO ONE LESS THAN THE NUMBER OF IDENTICAL
$      SUBSTRUCTURES
$ END LOOP 99
ALTER 50,54
ALTER 105,106
OUTPUT1 LAMA,,,,//C,N,-1/C,N,0$
$ PARAM //C,N,NOP/V,N,IP1=0 $ SIX TAPES
INPUTT1 /Q1,Q2,,,/C,N,-3/C,N,1 $ INP1 -- TWO TAPES
LABEL LOOP98$
$ PARAM //C,N,ADD/V,N,IP1/V,N,IP1/C,N,1 $ SIX TAPES
$ PRTPARM //C,N,0/C,N,IP1 $ SIX TAPES
$ INPUTT1 /Q,,,,/C,N,-3,V,N,IP1 $ SIX TAPES
INPUTT1 /Q,,,,/C,N,0/C,N,1 $ INP1 -- TWO TAPES
$ Q CORRESPONDS TO E IN LOOP99
PARTN PHIG,,Q/,PHIZ,,/C,N,1$
OUTPUT1    PHIZ,,,,//C,N,0/C,N,0$
REPT LOOP98,4$
SDR2 CASECC,CSTM,MPT,DIT,EQEXIN,SIL,,,BGPDT,LAMA,QG,PHIG,,/,
     OQG1,OPHIG,,,/C,N,REIG$
OFP OPHIG,OQG1,,,,//V,N,CARDNO$
ALTER 108,112
ALTER 114,115
ENDALTER
CEND
```

TABLE 1

Calculation Times for Substructuring Analysis of 5 Lashed 80-cm (31-in.) Steam Turbine Blades

Phase	Description of Run	Computer Field Length	CPU Seconds or CP Seconds	CRU Hours or CS Seconds
0	Generation of Airfoil Mesh Using MESH6	6500 200000$_8$	427	462 CS
I	Generation of Matrices for Substructure	370 500K	872	0.940 CRU
II	Combination of Matrices and Solution of Reduced Static Elastic Problem	370 500K	502	0.704 CRU
III	Preparation of Output Displacements, Forces and Stresses for Static Elastic Problem and Generation of Substructure Differential Stiffness Matrix	370 500K	2457	3.042 CRU
IV	Static Differential Stiffness Reduced Solution	370 520K	683	0.923 CRU
	Determination of Eigenvalues and Reduced Eigenvectors for Modes 1, 2, 3, 4 and 8 at 3600 rpm	370 520K	3852	2.128 CRU

TABLE 1 (Continued)

Phase	Description of Run	Computer Field Length	CPU Seconds or CP Seconds	CRU Hours or CS Seconds
IV Contd.	**Determination of Eigenvalues and Reduced Eigenvectors for Modes 5, 6, 7, 8, and 9 at 3600 rpm**	370 520K	3592	4.472 CRU
	Determination of Eigenvalues and Reduced Eigenvectors for Mode 4 at 3600 rpm	370 520K	1384	1.780 CRU
	Determination of Eigenvalues for Modes 1, 2, 3 and 4 at 0 rpm. No reduced Eigenvectors	370 520K	Computer	Error-No Charge
	Determination of Eigenvalues and Reduced Eigenvectors for Modes 5, 6, 7 and 8 at 0 rpm	370 520K	3487	4.177 CRU
	Determination of Eigenvalues and Reduced Eigenvectors for Modes 7, 8, 9 at 0 rpm	370 520K	2084	2.546 CRU
V	Stress Recovery for Static Differential Stiffness and Modes 1, 2, 3, 4 and 8 at 3600 rpm	370 500K	1179	1.866 CRU
	Stress Recovery for Modes 5, 6, 7, 8 and 9 at 3600 rpm	370 500K	860	1.400 CRU

TABLE 1 (Continued)

Phase	Description of Run	Computer Field Length	CPU Seconds or CP Seconds	CRU Hours or CS Seconds
V Cont.	Stress Recovery for Modes 5, 6, 7 and 8 at 0 rpm	370 500K	742	1.214 CRU
VI	Separate Data on the Two Discs Used to Enable Plotting in Smaller Runs. 2 Runs	370	100/run	.400 CRU/run
VII	Stress Plotting on both Surfaces of Airfoil of Either Maximum and Minimum Principal Stresses or X and Y Stresses Using NASPLT. 30 Runs.	370 350K	137/run	.150 CRU/run
	Stress Plotting on both Surfaces of Outer Lashing Wire of Maximum Principal, Minimum Principal, X and Y Stresses Using NASPLT. 15 Runs.	370 350K	75/run	.099 CRU/run
	Stress Plotting on Both Surfaces of Inner Lashing Wire of Maximum Principal, X and Y Stress Using NASPLT. 15 Runs.	370 350K	69/run	.094 CRU/run
TOTAL			28600	462 CS 33.4 CRU

TABLE 2

Estimated Calculation Times for Non-Substructuring Analysis of 5 Lashed 80-cm (31-in.) Steam Turbine Blades Using Level 15 NASTRAN on the IBM 370-165 Assuming Adequate Disk and Core Space Were Available

Phase	Description	Field Length	CPU Seconds	CRU Hours
0	Generation of Airfoil Meshes	-	-	-
I	Form Matrices	500K	1260	1.4
II	Solve Elastic Static Problem	500K	1170	1.5
III	Output Elastic Results and Create Differential Stiffness Matrix for Blade Set	500K	10500	7
IV	Differential Stiffness Static Solution	500K	1170	1.5
	Natural Frequencies and Eigen-vectors (13 Modes)	850K	8000/mode	11/mode
V	Stress Recovery	Same as with Substructuring		
VI	Separation of Data on Discs	Same as with Substructuring		
VII	Plotting Isostress Lines	Same as with Substructuring		
TOTAL			124000	162

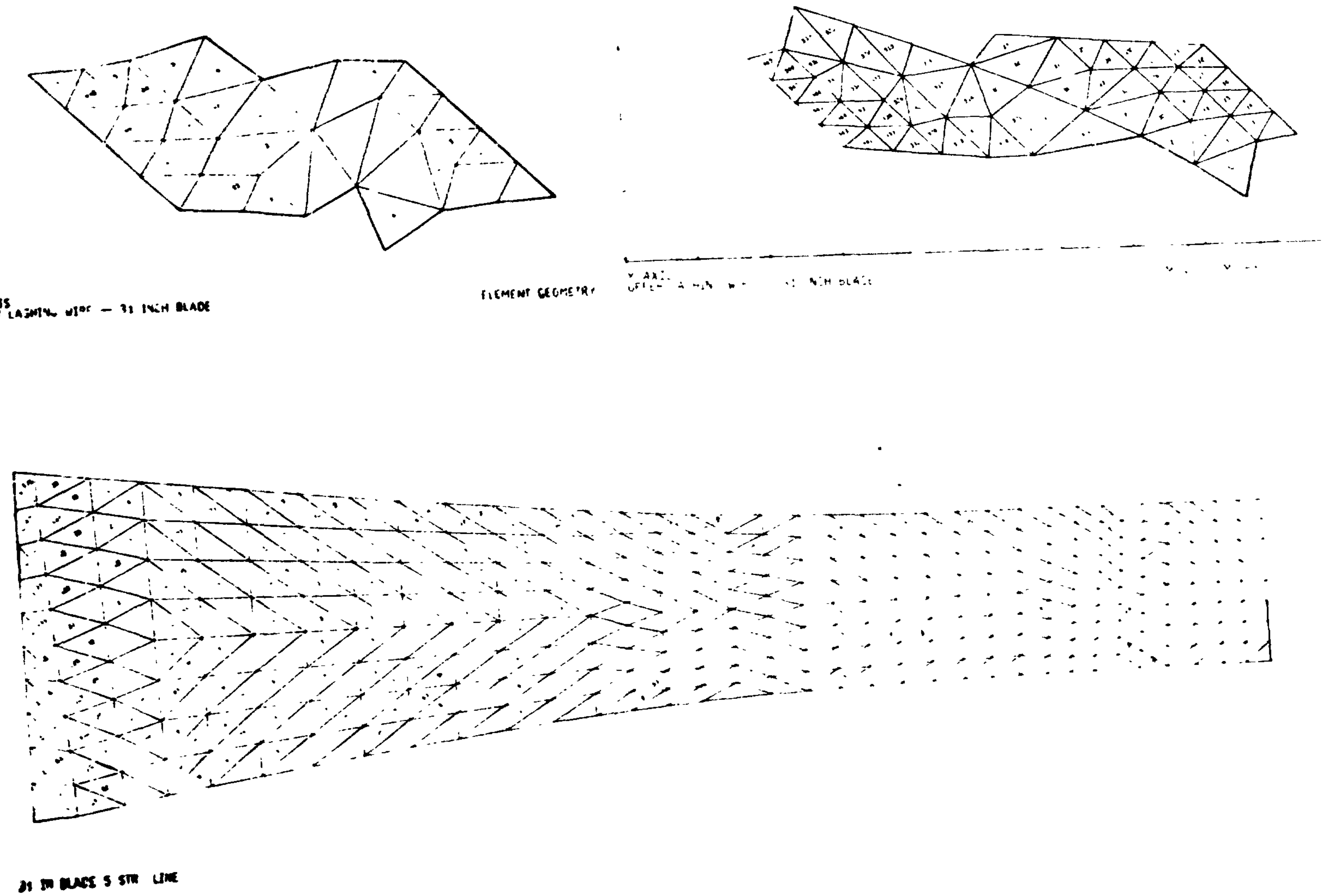

Figure 1 - Finite Element Mesh for Airfoil and Lashing Wires.

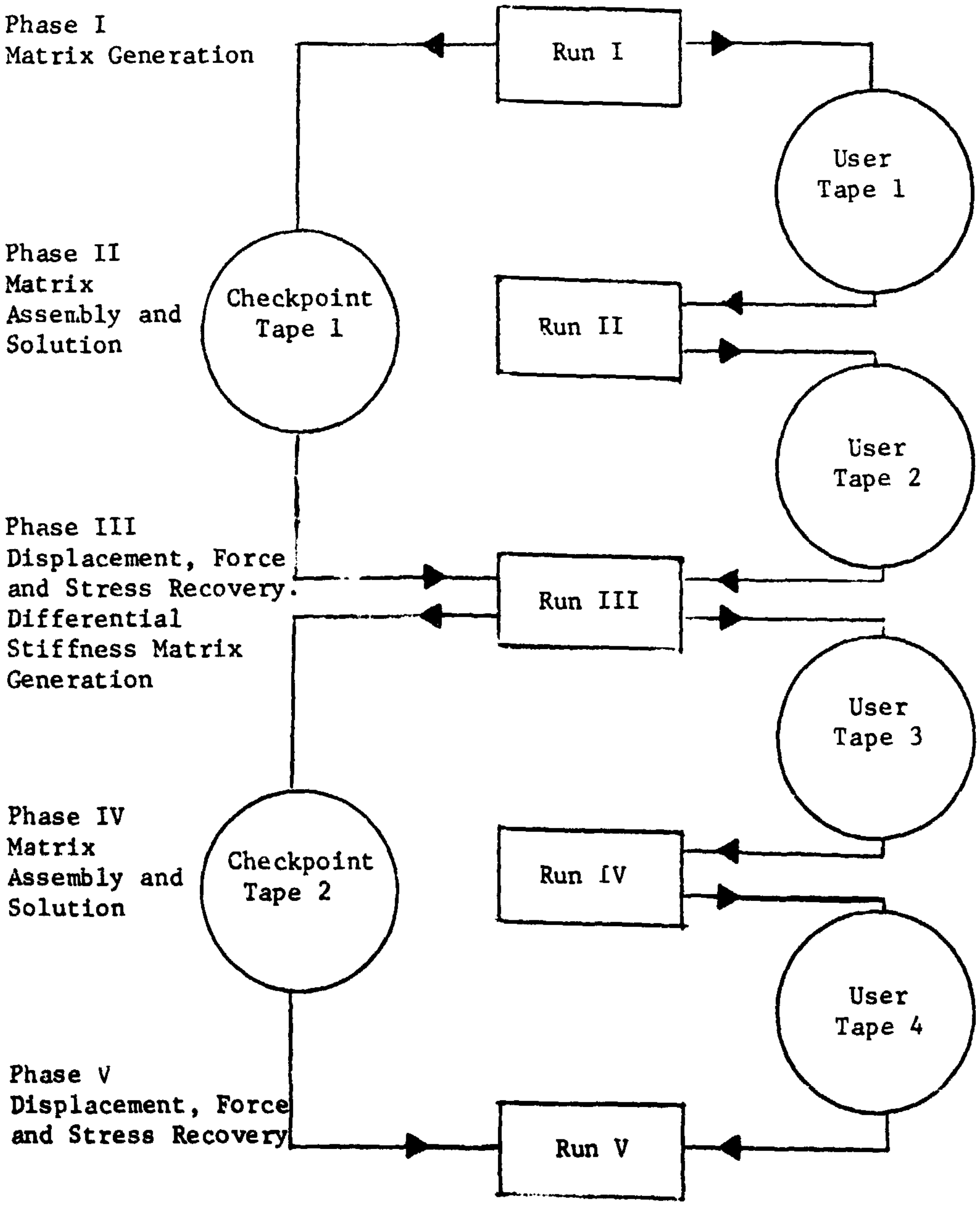

Figure 2 - Substructure Runs for Static or Dynamic (Natural Frequency) Analysis, with Differential Stiffness, of Identical Substructures.

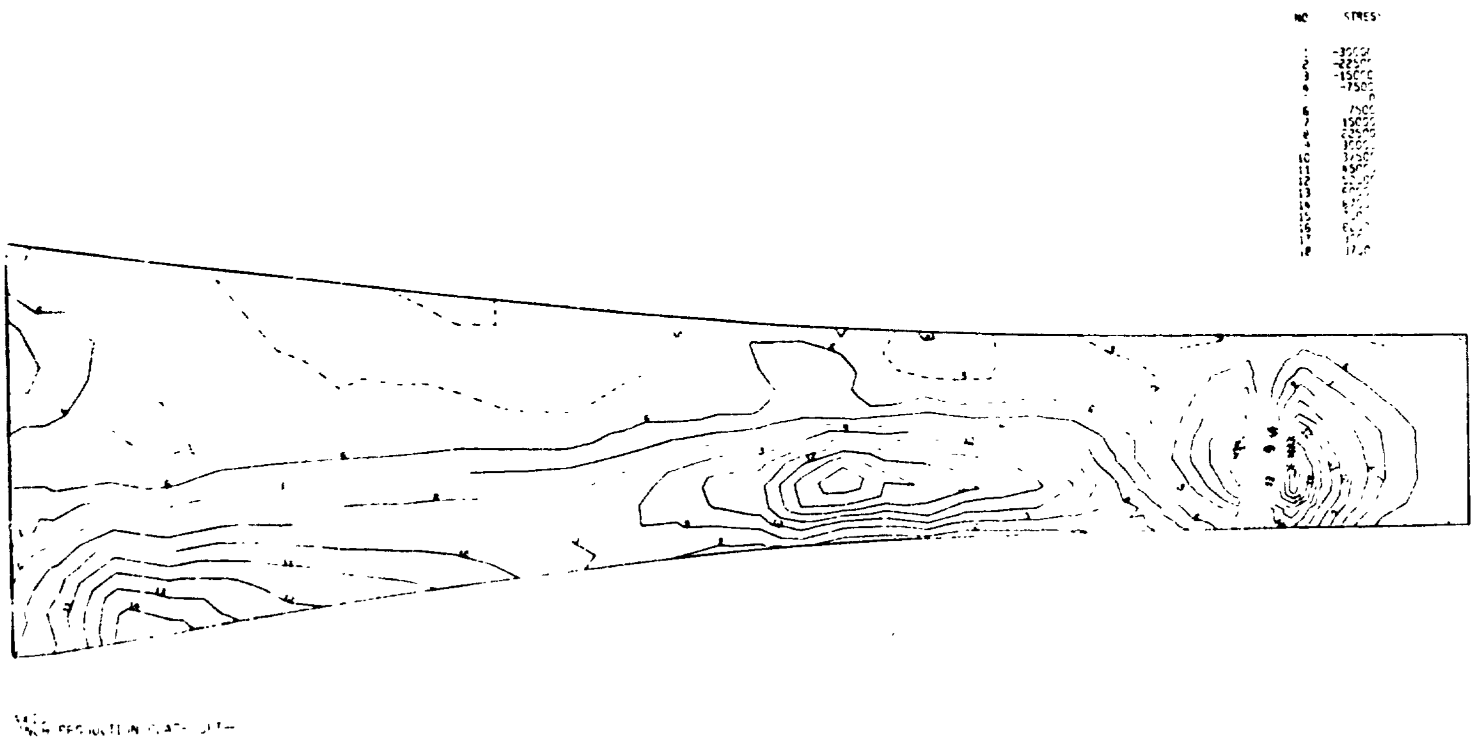

Figure 3 - Sample Isostress Pattern on Surface of Airfoil.