# NASA Contractor Report 3105



# Experiments on Multiplane Balancing Using a Laser for Material Removal

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# Experiments on Multiplane Balancing Using a Laser for Material Removal

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# I. SUMMARY

The purpose of this report is to summarize the results performed under Task V and Task VI of NASA Contract NAS3-18520. The following tasks were investigated:

Task V - Modification of Rotor System for Laser Balancing Demonstration

A. From the laser investigations previously performed under NASA Contract NAS3-14420, a laboratory rotor was redesigned to accept balancing corrections using a laser metal removal method. The existing test rig was then modified to allow for a laser metal removal procedure for rotor balancing.

B. The laser set-up hardware required to balance the rotor using two correction planes was selected.

C. A test laser for suitable balancing demonstration was selected and leased. The variables associated with the test laser which must be controlled by the existing balancing system were also identified.

D. Based on the existing rotor's balancing requirements, the proportionality factors relating unbalance to laser energy release were determined.

Task VI - Rotor Balancing Using the Laser Material Removal Method

A. The laser capabilities were calibrated as to the amount of material removed for variations in rotor speed, number of pulses, energy level, and type of lens.

B. The rig hardware including the laser head, supporting structure, lens, and mirrors was assembled.

C. The rotor was balanced through the first bending critical speed using the laser material removal procedure to apply trial weights and correction weights.

D. The rotor was purposely unbalanced to simulate a distributed unbalance condition which excited the first bending critical speed.

E. Rotor amplitudes before and after balancing, trial and correction weights, rotor speeds during operation of laser, time required for balancing, and other pertinent test parameters were documented.

Mr. Albert Battista, President of Laser, Inc., and Mr. William Shiner provided information on the laser performance and assisted in reconfiguring the laser power supply and analyzing the resultant effects.

# II. DETAILS OF LASER SYSTEM

## General

The Laser Incorporated Model 11 laser head utilizes a neodymium-doped laser rod with an emission wavelength of 1.06 micrometers. The unit is a reliable system capable of 25 joules of output at a rate of 30 pulses per minute. The Model 11 laser head consists of two major subassemblies:

1. Laser module and mirrors
2. Power supply

## Laser Module and Mirrors

The laser module consists of a water cooled dielectric tube which contains two Xenon flashlamps, a neodymium (ND) glass laser rod, a silver reflector, and a filter tube. The filter tube is required over the laser rod for protection from ultraviolet light produced by the flashlamps.

In operation, both flashlamps and laser rods are cooled with de-ionized water which is flowed through the cavity via water connections contained in the outer dielectric housing. The laser mirror assemblies are constructed from aluminum and feature a three-point, spring-loaded suspension system. Nylon dust covers are mounted on both assemblies and extend to the laser rod for dust protection.

## Laser Specifications

Laser specifications are as follows:

| | |
|---|---|
| Lasing Wavelength: | 1.06 micrometers |
| Energy Output: | 25 to 40 joules at 30 pulses per minute, 1 millisecond duration |
| Beam Divergence | Less then 15 milliradians full angle, half energy at rated output |

## Power Supply

All of the operational features of a Model 11 laser are controlled by the power supply. This unit serves three functions as listed on the following page.

1. It provides the energy storage necessary for proper operation of the laser.
2. It includes all the operational controls for the system.
3. It includes the laser water cooling assembly.

The power supply is completely solid state. The supply is capable of delivering approximately 1200 watts of power to the laser, i.e., 1200 joules at 1 pulse per second.

## III. CALIBRATION OF MATERIAL REMOVAL RATES

### Static Removal Rate and Process Description

A laser system with an output of 25 joules and a pulse duration of $1 \times 10^{-3}$ seconds has a corresponding peak power of 25,000 watts. A typical beam divergence of this system is less then 15 milliradians. If a lens of 4 in. (10 cm) focal length is used to focus the energy, the spot area exposed to the focused laser beam becomes $0.49 \times 10^{-3}$ in.$^2$. A 25,000 watt beam focused onto an area of $0.49 \times 10^{-3}$ in.$^2$ results in a density of $51 \times 10^6$ watts/in.$^2$. A power density of this magnitude is sufficient to vaporize any known material.

Not all of the material is removed by evaporation, however, as shown in Figure 1; laser machining is basically a high speed ablation process. The evaporation of a very small portion of liquid metal takes place so rapidly under the high intensities of a focused laser beam that a substantial impulse is transmitted to the liquid. Material leaves the surface not only through evaporation, but also in the liquid state at a relatively high velocity. Figure 2 shows the particles being removed from a rotating disk.

The amount of energy needed to raise a volume of material such as stainless steel to its vaporization point can be calculated approximately as the energy required to raise the metal to its vaporization point plus the latent heats of fusion and vaporization, as shown. The energy required for vaporization of 1.0 gm of metal requires:

a. Heating from room temperature to melting point

$$E_1 = C(T_m - T_o) = 0.11(1535 - 20) = 167 \text{ calories}$$

b. Changing from solid to liquid at $T_m$

$$E_2 = L_f = 65 \text{ calories}$$

c. Heating from melting point to boiling point

$$E_3 = C(T_b - T_m) = 0.11(3000 - 1535) = 161$$

d. Changing it from liquid to vapor at $T_b$

$$E_4 = L_v = 1630 \text{ calories}$$

and $E_1 + E_2 + E_3 + E_4 = 2023$ calories $= 8500$ joules per 1 gram

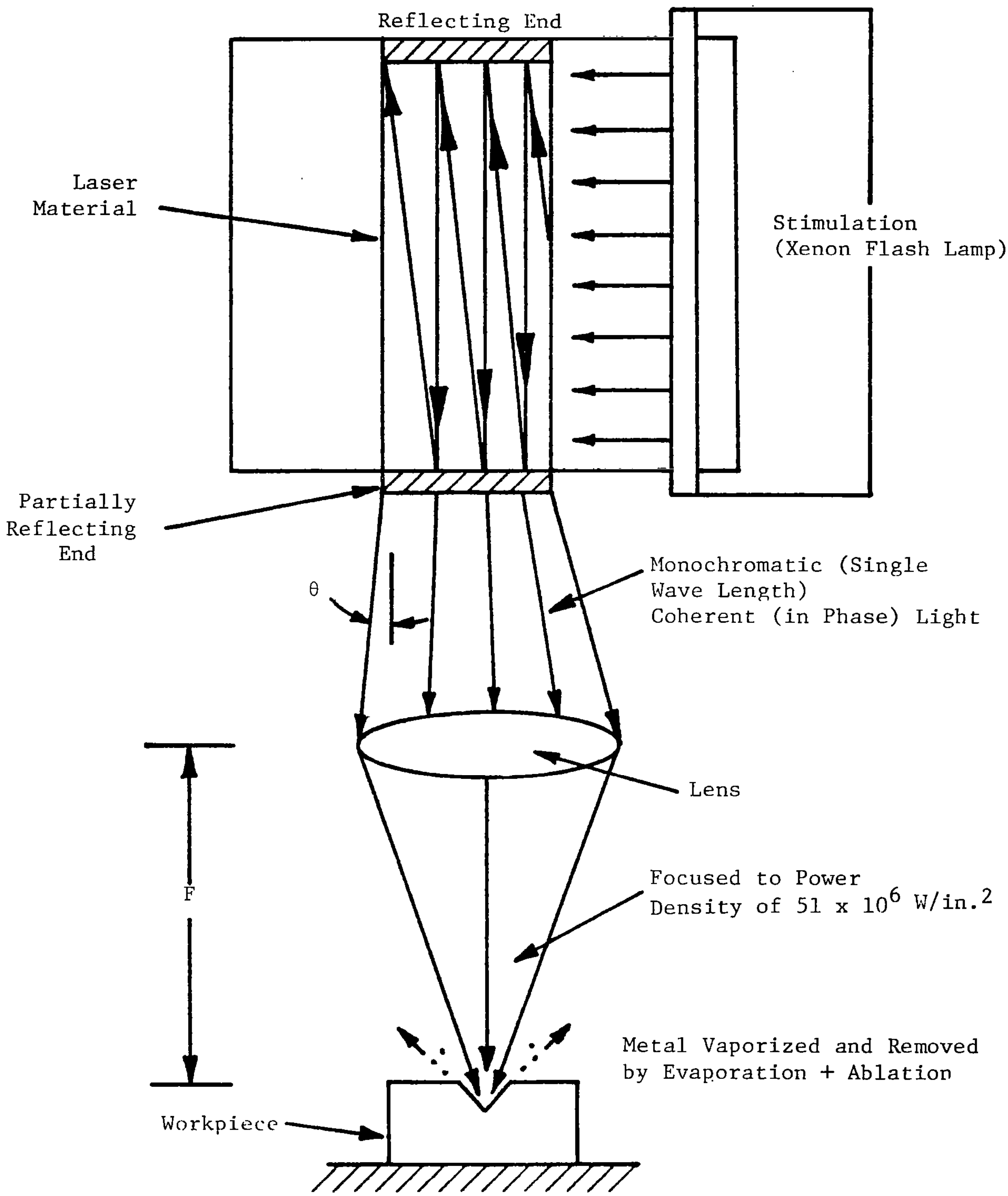



Fig. 1 Laser Removal Process Drilling

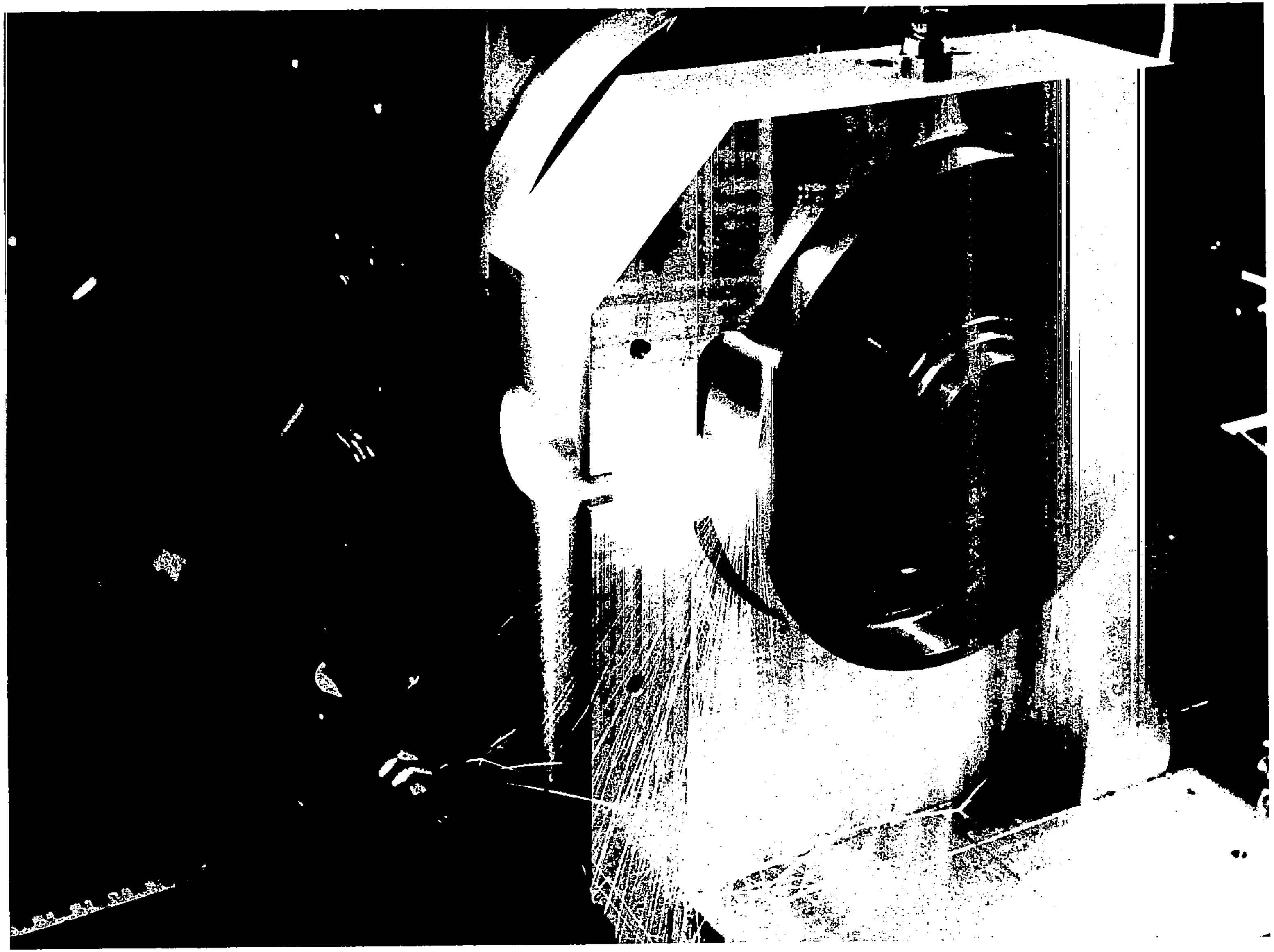


Fig. 2  Material Removal from Rotating Target

where:

$C$ = specific heat in calories/gm

$T_o$ = ambient temperature in °C

$T_m$ = melting temperature in °C

$T_b$ = boiling temperature in °C

$L_f$ = heat of fusion in cal/gm

$L_v$ = heat of vaporization in cal/gm

The output energy is on the order of 35 to 40 joules:

$$\frac{35}{8500} = 0.0041 \text{ gm removed} \qquad \frac{40}{8500} = 0.0047 \text{ gm removed}$$

This gives close agreement with the experimental results of between 4.1 - 5.1 mg.

Dynamic Removal Rate

Using a test rig shown in Figures 3 and 4, calibration of material removal rates was experimentally determined. The experimental rotor has three disks and is supported by two oil film journal bearings. An electric motor provides the variable speed drive. Figure 5 shows a cross section of the test rig. On the left-hand side is the overhung disk. This disk is referred to in this text as Plane 1. Sacrificial rings were attached to this disk for the balancing experiments. The housing which surrounds the disk is used as a containment device and a probe holder. Horizontal and vertical proximity probes were used to record vibration response in Plane 1. The journal bearing next to the overhung disk is a tilting pad bearing which uses silicone (5 centistokes viscosity) as the working fluid. This bearing is Plane 2. The center disk acts as a thrust bearing for this demonstration rig. There are also displacement probes at this location to record response at the disk which is identified as Plane 3.

The journal bearing between the center disk and the motor end disk is identical to the one between the overhung disk and the center disk. This location is Plane 4. The bearing arrangement and working fluid were purposely selected to

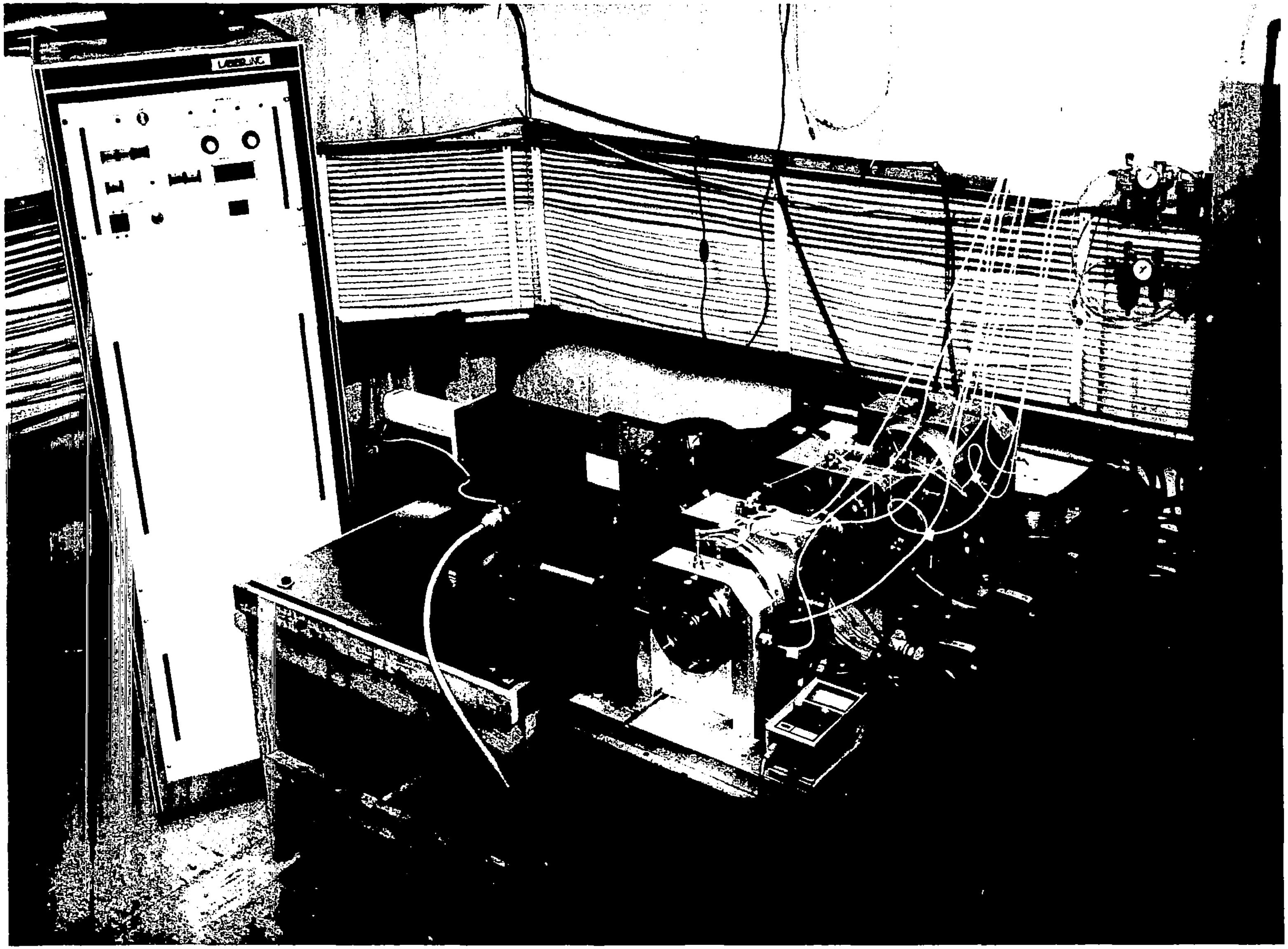
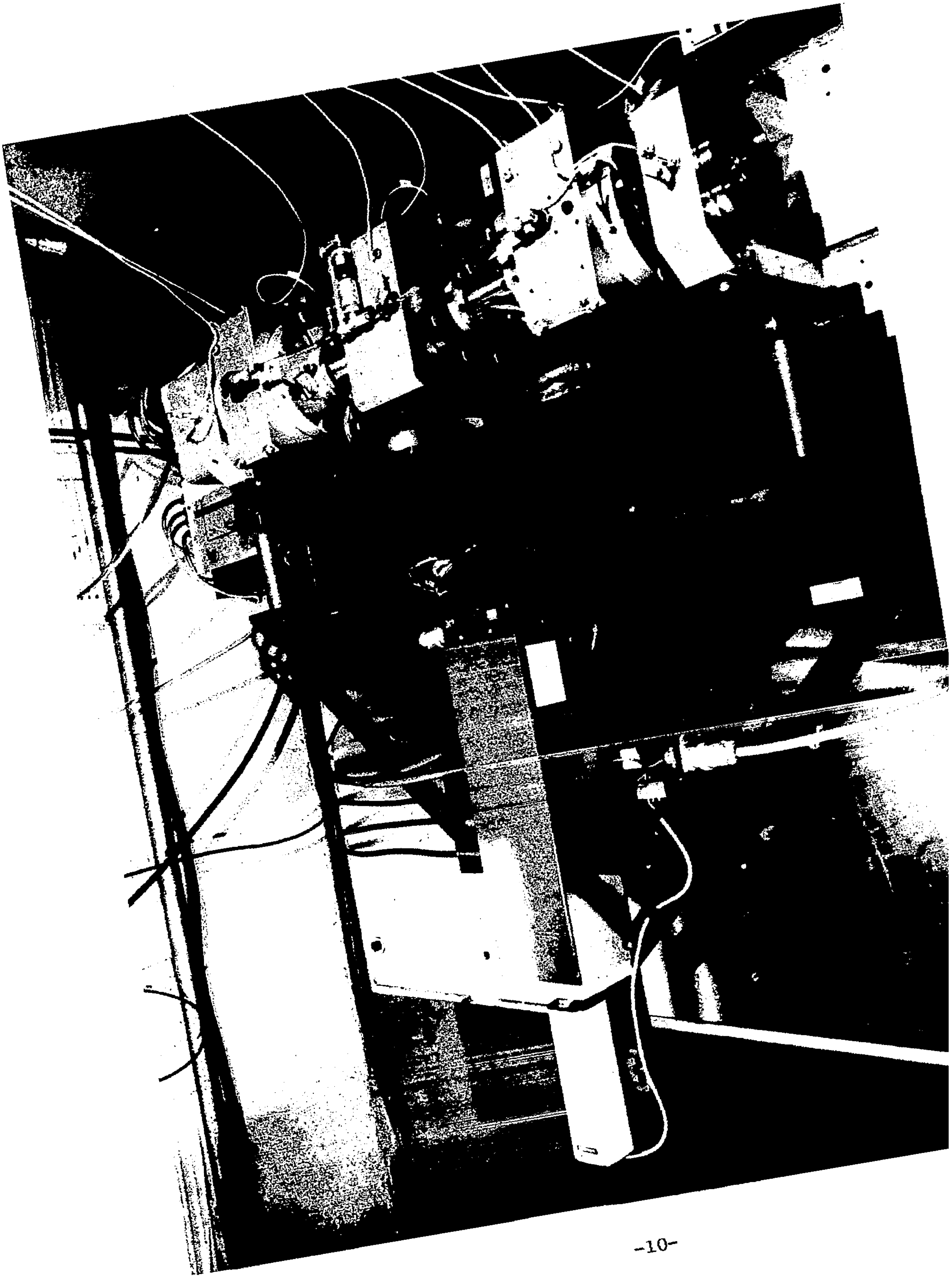


Fig. 3 Test Rig with Laser Power Supply and Optical Assembly



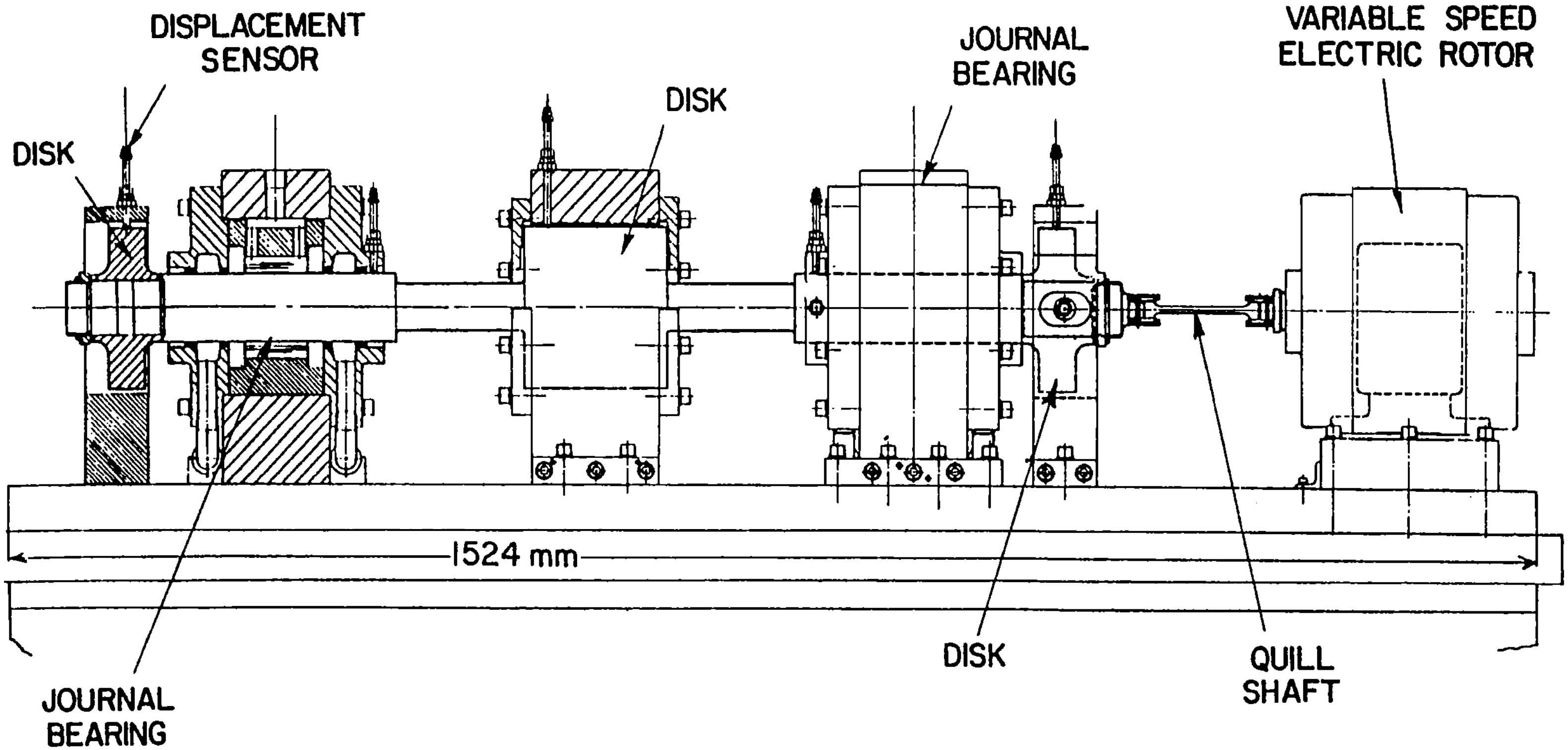



Fig. 5 Test Rig Assembly Cross Section

cause a very sensitive bending critical speed within the operating range. The motor end disk is the same as the overhung design. This location also has sacrificial rings attached for laser-applied trial and correction weights. Again, a housing was used for containment and probe mounting. This balancing location is referred to as Plane 5. This rotor is attached to a 30-hp, variable-speed motor by means of a quill shaft. This quill shaft has crowned teeth which can accept normal misalignment without exhibiting indications of friction-induced instabilities.

As mentioned above, attached to the overhung and motor end disks were sacrificial rings which are easily removed by three screws. Several of these rings were made for test specimens. When the laser beam was focused directly on the surface of the rotor, the concentration of energy resulted in deep penetration of the rotor wall.

Using a thick wall rotor, focused beam removal rates were investigated. This was done by taking a fixed number of shots at each indexed portion of the optical assembly. Several indexes were made before recording the final specimen weight. Knowing the weight change and total number of shots, the weight per shot can be determined and is shown in Figure 6 as a function of rotor speed. For a given pulse duration at slow speeds, more metal is removed because the beam covers less of the rotating surface in this time duration.

The removal of material also is dependent on reaching the threshold energy level for vaporization. Since the laser power supply wattage is limited, reducing the pulse duration results in decreased metal removal rates. Also, as the depth of the beam penetration increases, the amount of material removed decreases. Generally, this limit of depth at 1 millisecond pulse duration is on the order of 3-4 millimeters, since the beam becomes unfocused at greater depths.

Target Material

As shown previously in Figure 2, the target consisted of a sacrificial ring 6.25 inches in diameter (outside diameter). The inside diameter was 5.875 inches. The ring was attached to the rotor by 3 Allen head cap screws, which allowed replacement of the rings from the rotor.

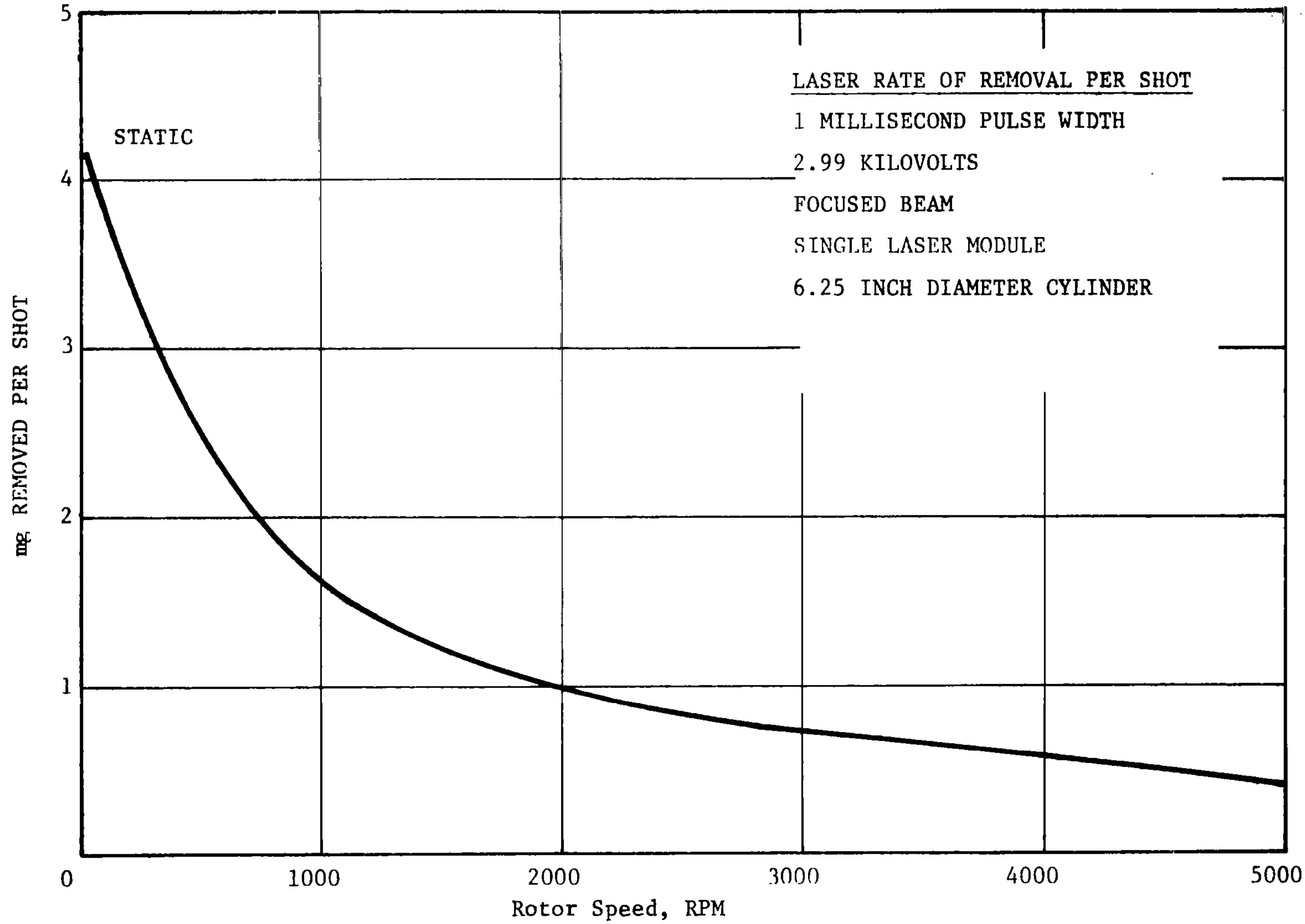



Fig. 6 Rate of Material Removal per Shot

The material and specifications were:

Alloy Steel

AISI 4130

Harden to $R_c$ 32-36

| | | |
|---|---|---|
| Width of Target Zone | - | 1.12 inches |
| Outside Diameter | - | 6.25 inches |
| Inside Diameter | - | 5.875 inches |

## IV. USE OF LASER BALANCING COMPUTER PROGRAM

### Laser Hardware Check-Out Program

Two proprietary MTI computer codes are described in this section. The first is a hardware check-out routine for the laser balancing system. It is an interactive program which can be run in two modes: manual or automatic. It is mandatory to run through the entire set of laser commands in the manual mode at least one time successfully before attempting to run in the automatic mode. Figure 7 illustrates the control panel used to operate this program, and Figure 8 is a schematic of the system.

### Check-Out Procedure

The program executes after RUN LASER is entered. A list of eight functions (numbered 0 through 7) is printed: STOP, CLEAR, MIRROR, DIRECTION & INDEX, PHASE ANGLE, FIRE, AUTOMATIC, and RESTART. Functions 1 through 6 are described as follows.

Function 1 - CLEAR: this command sets the position of the laser to the center of the table, position zero. This is the initial position before each run.

Function 2 - MIRROR: the operator is requested to choose in which position (Plane 1 or Plane 2) he wants the mirror to be placed; that is, whether material will be removed from plane 1 or plane 2 of the rotor.

Function 3 - DIRECTION & INDEX: the operator is requested to enter the axial direction in which he wants the laser to move and by what increment.

Function 4 - PHASE ANGLE: the operator is requested to enter the phase angle in degrees. The angle resolution is six degrees and referenced from the shaft tachometer rotor zero point (also known as the key phaser).

Function 5 - FIRE: the operator is requested to enter a number to determine the maximum number of shots fired by the laser.

Function 6 - AUTOMATIC: this procedure automatically sequences through functions 1 - 5 without any operator intervention.

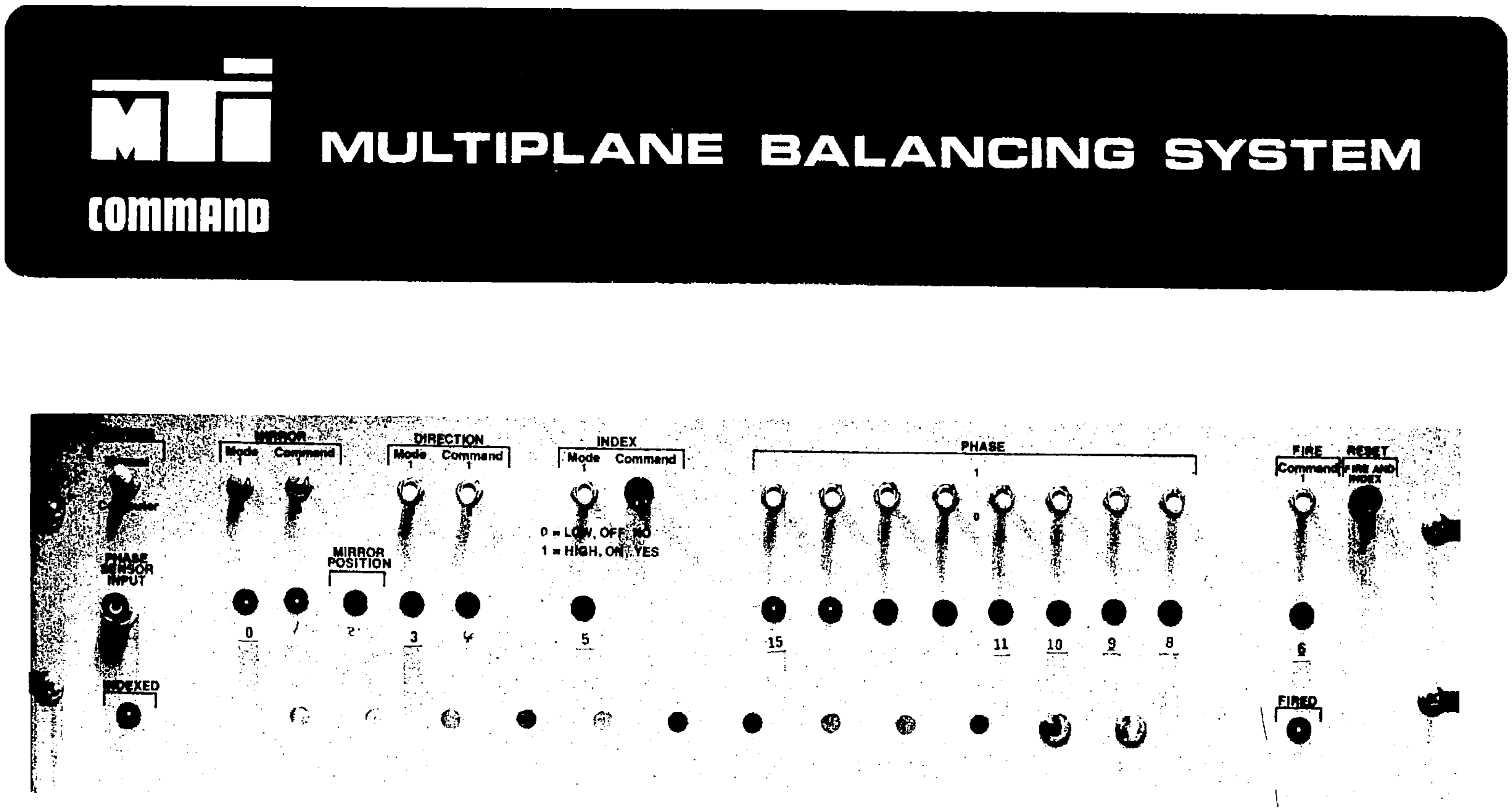



Fig. 7 Multiplane Balancing System

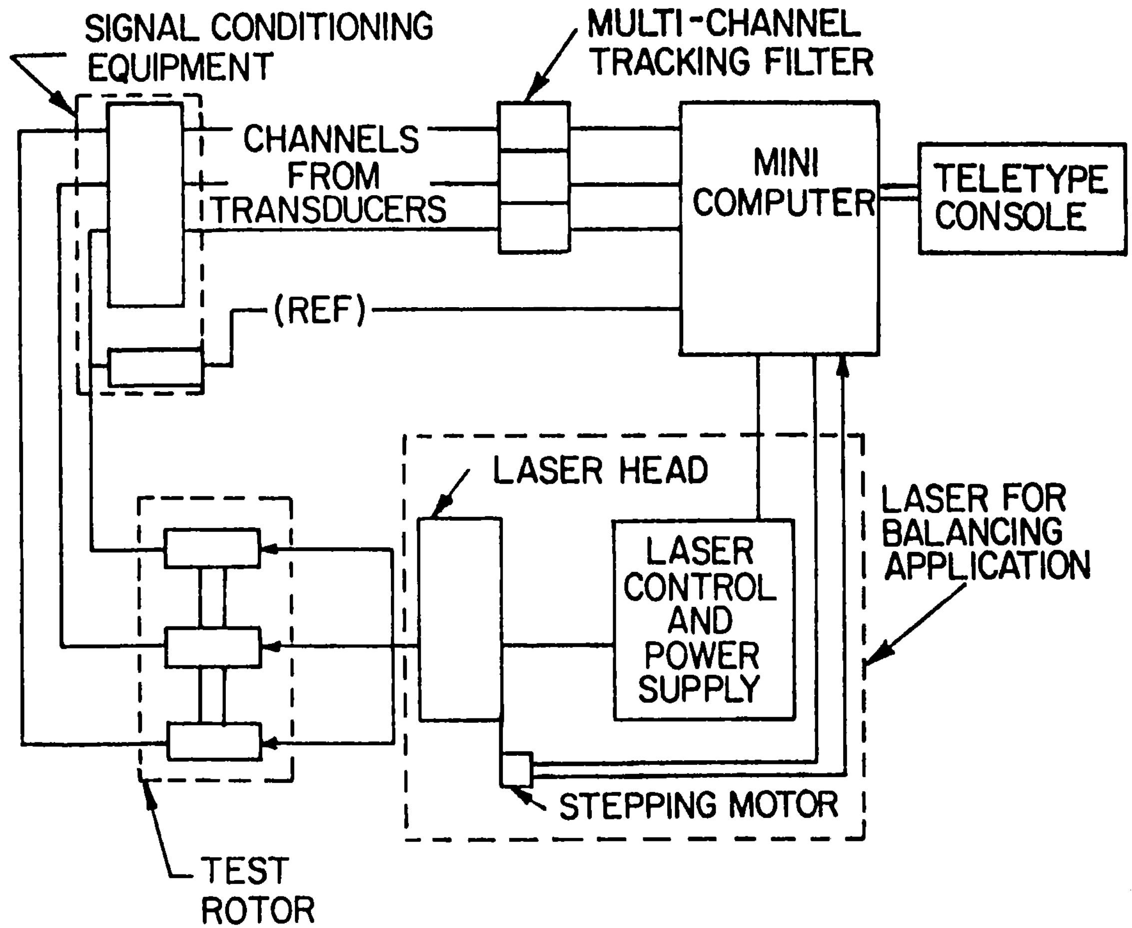



Fig. 8 Schematic of a Fully Automatic Flexible Rotor Balancing Installation with Laser and Minicomputer

When proceeding through the program in the manual mode, it is important to follow a certain sequence in performing the five functions. CLEAR should always be executed first, then MIRROR, DIRECTION & INDEX, and PHASE ANGLE can follow in any order desired. Only after these four functions have been executed successfully will it be possible to execute the function FIRE.

After this initial sequence of functions has been performed, the operator may now change the PHASE ANGLE and then immediately FIRE, or change the DIRECTION & INDEX and then re-FIRE, or change the MIRROR and re-FIRE without having to execute all four functions in a specific sequence again.

An example of the hardware check-out routine is shown in Figure 9. This program permits a series of commands to activate the hardware for single or multiple firings to the target.

## Laser Balancing Program

The MTI Laser Balancing Program has been installed on the MTI PDP 11/34 Computer System and is accessible to a satellite balancing station at the laser location. Besides the vibration sensors, several other pieces of data are required to perform the balancing procedure. The system requires a reference signal which defines a zero position on the rotor. From this zero position, the program uses that reference to time the firing of the laser pulse and calculate the proper angle for corrections. In addition, the operator must have defined the maximum number of shots at each axial location.

The program will obtain influence coefficients by first pulsing the laser with multiple shots at a given angular location on the shaft. This procedure is then repeated for a prespecified quantity of shots in all the other balancing planes. The computer program records the change in vibration amplitude and phase angle on all sensors for the total of shots at a given angular location on the shaft. The quantity of shots is equivalent to removal of a weight from the rotor.

By subtracting the corresponding results for the uncorrected rotor and dividing by the value of the trial weight, a set of sensitivity data or influence coefficients is obtained, one for each sensor at each speed. Since the measurements have both amplitude and phase angle, they must be treated as

```
 RUN DK1:[200,200]LASER

LASER HARDWARE CHECK OUT PROGRAM.

 DATE OF REVISION 3/16/78  REVISION 1
 FUNCTIONS:  1 = CLEAR
             2 = MIRROR
             3 = DIRECTION + INDEX
             4 = PHASE ANGLE
             5 = FIRE
             6 = AUTOMATIC
             7 = RESTART
             0 = STOP
ENTER MAXIMUM NUMBER OF SHOTS PER INDEX POSITION   10

FUNCTION?   1

CLEAR COMMAND

FUNCTION?   2

MIRROR COMMAND
ENTER DESIRED MIRROR POSITION (1=PLANE #1    2=PLANE #2)   1

FUNCTION?   3

DIRECTION + INDEX COMMAND
ENTER DIRECTION  (1=PLANE #1   2=PLANE #2)   1

ENTER AMOUNT OF INDEX   4

FUNCTION?   4

ENTER PHASE ANGLE IN DEGREES   99

FUNCTION?   5

FIRE COMMAND
ENTER NUMBER OF SHOTS TO BE TAKEN   14

FUNCTION?   0

LOCATION OF LASER WITH RESPECT TO
CENTER OF DISK IS ,     0
TT2  --  STOP
```

Fig. 9  Hardware Checkout Computer Printout vectors. Hence, the influence coefficients likewise will be vectors which define the resulting change in amplitude and phase angle at the sensors for the given speeds, per unit mass unbalance, or per quantity of laser shots in the particular balancing plane.

Once all the influence coefficients are obtained, the correction shots required to minimize the unbalance vibration of the rotor are computed by the program. The computer controlled laser system then will remove weight while the rotor is running.

It is important to recognize that the program assumes the measured vibrations to be caused by the mass unbalance of the rotor. This assumption implies that the vibrations are considered to be synchronous with the rotational speed. Hence, the measured input data to the program must include only the once-per-revolution component of the vibration which, in most cases, means that the sensor signals must be filtered, as was done for these experiments.

Phase Delay of System

The FIRE command is routed through the interface and laser positional control circuitry and runs to the laser fire and power control. Inherently, the issuance of this command does not instantly fire the laser. Delay in the interface circuitry as well as discharge time for the Xenon flashlamps in the laser causes a delay in firing. This delay is experimentally corrected by issuing a command to fire at the same phase angle at different rotor speeds. Noting the burn zone initiating point, this angle was found to be $2.03 \times 10^{-3}$ degrees per RPM. It should be noted that the computer software compensates for this phase angle delay during balancing. From this same test, Figure 10 was determined. This graph shows the burn zone in degrees of circumference as a function of speed.

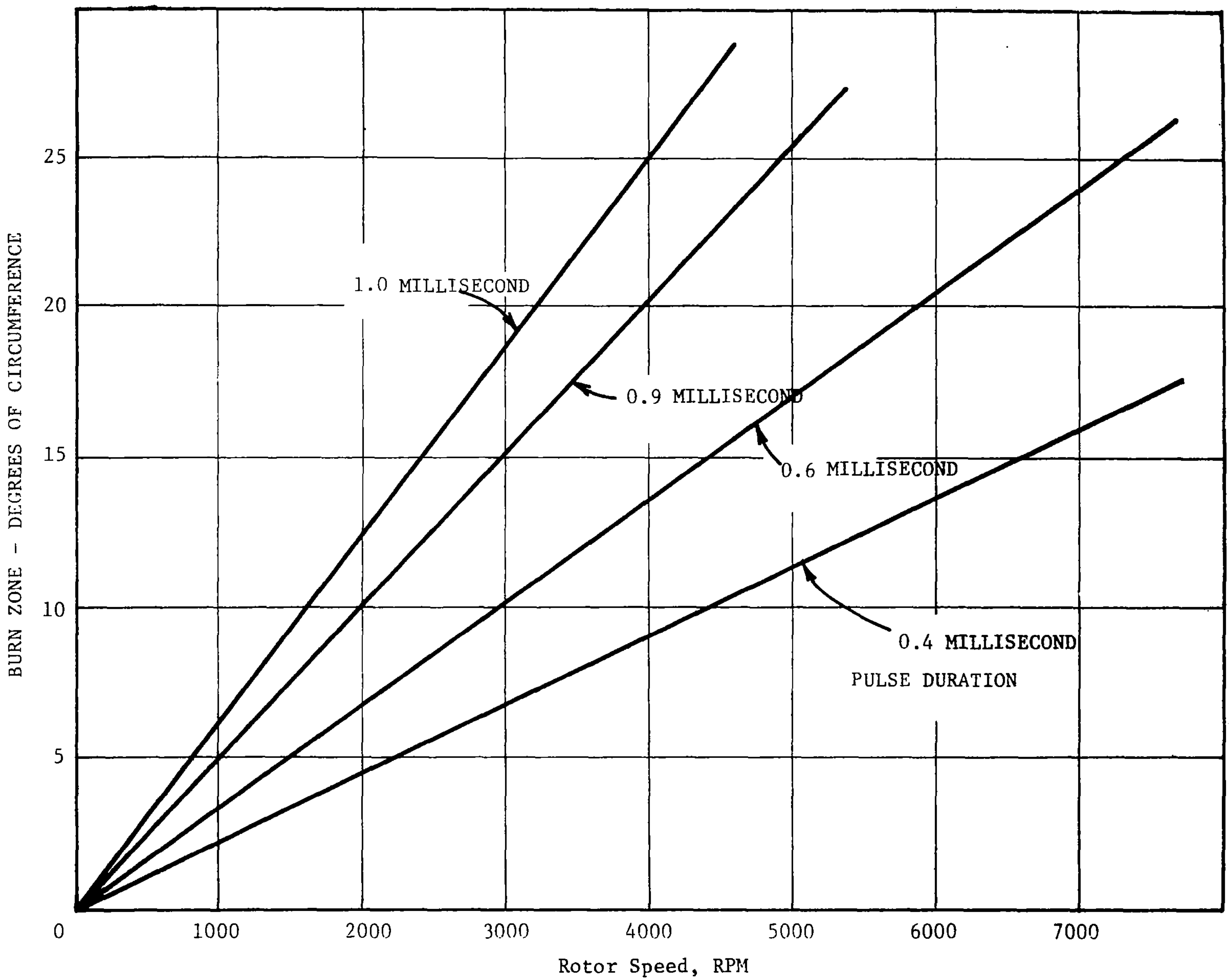



**Fig. 10** Burn Zone Versus Speed for Laser Pulse Duration - 6.25 Inch Diameter Cylinder

## V. DEMONSTRATION OF BALANCING PROCEDURE AND PRELIMINARY TESTS

### Laser Hardware Check-Out Program - Static

The laser check-out program was initiated to clear all channels and verify the starting parameters. The check-out program is used to test the laser hardware. No shots were fired for this test run.

### Laser Balancing Program - Simulated Rotor Data

Once the starting point was verified, a simulated test case was completed using data input by the operator rather than from the rig. A simulated rotor data operation uses rotor data input from the key-board rather than from the data acquisition system.

### Laser Hardware Check-Out Program - Dynamic

This was used to witness the tangential particle removal characteristics of this system. This was not part of the balancing operation but was used to show the material removal process.

### Balancing Demonstration

With the use of displacement type sensors, the out-of-roundness data was recorded at 2300 rpm. The rotor was then manually accelerated until the first bending critical speed was encountered. The rotor could not traverse this resonance in the initial unbalanced condition. The uncorrected rotor data was then automatically acquired by the minicomputer at 6300 rpm which is just below this bending mode. Figure 11 shows the program printout for the balancing demonstration with displacement sensors.

As part of this study, it was necessary to take rotor sensitivity or influence coefficient data manually before attempting the laser balancing system and to give us an understanding of the response characteristics to the first critical speed. Figure 12 shows the response of the rotor system with varying amounts of unbalance weights. The nonlinear damping characteristics of the rotor-bearing system are shown by adding weight in a correction plane and then adding weight 180° to this location. These weights were added by wax. The results show nonlinear response in the critical speed range of 6300 - 6500 rpm.

```
>RUN DK1:[200,200]LASBAL
*********************************************************************

MTI  LASER BALANCING SYSTEM
DATE OF REVISION 2/28/78   REVISION NUMBER 5
SYSTEM DIRECTIVES WITH EXPLANATION
PORTION OF DIRECTIVE ENCLOSED BY () IS OPTIONAL
     PR(OGRAM) - PROGRAM COMPUTER FOR NEW ROTOR SYSTEM
     RE(PEAT)  - BALANCE A NEW ROTOR AFTER USING PR DTR.
     ST(OP)    - PROGRAM EXECUTION IS TERMINATED

ENTER DIRECTIVE - PR

 28-FEB-78   16:49:39

ENTER DR NUMBER (DR0 OR DR1) 1

ENTER FILENAME FOR ROTOR SYSTEM SETUP DATA   DK1:[200,200]DATAL.DAT
*********************************************************************

DATA ACQUISITION

ACQUISITION OF OUT OF ROUNDNESS DATA


SET ROTOR SPEED AT       2300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D

DATA FOR UNCORRECTED ROTOR

SET ROTOR SPEED AT       6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D

DATA FOR TRIAL WEIGHT IN BALANCING PLANE    1

SET ROTOR SPEED AT       750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D

   MAX. SHOTS PER INDEX POSITION=    20
   MAX. NUMBER  OF INDEXES=   15
   LASER DELAY ANGLE =     1.57
   MIRROR COMMAND PLANE #  1
   ENTER PHASE ANGLE IN DEGREES    40
   FIRE COMMAND ENTER NUMBER OF SHOTS TO BE TAKEN    60
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

  TRIAL WEIGHT:      60. SHOTS   IN    40.00 DEGREE LOCATION

 28-FEB-78   16:58:27

SET ROTOR SPEED AT       6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D

DATA FOR TRIAL WEIGHT IN BALANCING PLANE    5


SET ROTOR SPEED AT       750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D

   MAX. SHOTS PER INDEX POSITION=    20
   MAX. NUMBER  OF INDEXES=   15
   LASER DELAY ANGLE =     1.47
   MIRROR COMMAND PLANE #  5
   ENTER PHASE ANGLE IN DEGREES    200
   FIRE COMMAND ENTER NUMBER OF SHOTS TO BE TAKEN    60
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

  TRIAL WEIGHT:      60. SHOTS   IN   200.00 DEGREE LOCATION

 28-FEB-78   17:04:28
```

Fig. 11 Program Printout for the Balancing Demonstration

```
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D
STOP ROTOR

                                  SUMMARY

 28-FEB-78    17:06:17

     READING     SPEEDS     PLANES
         2          1          2

     SENSOR NUMBERS USED IN BALANCING
                    1
                    5

     PLANE   NUMBERS USED IN BALANCING
                    1

     AMPLITUDE CALIBRATION FACTORS

      SENSOR      MULTIPLY      MULTIPLY       ADD TO
        NO.     AMPLITUDE        PHASE         PHASE
              MILS PER VOLT                   DEGREES

         1        2.8280        1.0000        90.0000
         5        2.8280        1.0000        90.0000

 OUT OF ROUNDNESS DATA

SENSOR     AVE SPEED     AMPLITUDE        PHASE
              RPM       MILS PK-PK      DEGREES

     1       2304.9        1.1382        81.3994
     5       2307.2        0.8421       107.9445

MEASURED DATA  --  UNCORRECTED ROTOR

                          MEASURED VIBRATION              NET VIBRATION
SENSOR     AVE SPEED     AMPLITUDE        PHASE     AMPLITUDE        PHASE

     1       6317.0        1.5260      115.4976       0.8646      163.0616
     5       6317.2        1.6413      135.9435       0.9809      159.7108

 TRIAL WEIGHT  --          60.0 SHOTS
PLANE NO.  1             40.00 DEGREES

 SENSOR     AVE SPEED     AMPLITUDE        PHASE

     1       6298.7        1.4593      112.1158
     5       6297.8        1.4512      134.8513

 TRIAL WEIGHT  --          60.0 SHOTS
PLANE NO.  5            200.00 DEGREES

 SENSOR     AVE SPEED     AMPLITUDE        PHASE

     1       6288.1        1.3970      103.2195
     5       6296.3        1.3927      126.8990

INFLUENCE COEFFICIENTS
REAL PART
   0.11001E-02  -0.36470E-02   0.78703E-03  -0.34176E-02

IMAGINARY PART
  -0.14759E 02   0.11839E-02  -0.31073E-02  -0.26228E-03
 CORRECTION WEIGHTS  --  SET NO.  1

 TOTAL WEIGHT AT ANGLE
    SHOTS       DEGREES

     127.8        33.33
      80.8       168.12

  CHECK BALANCE RUN
IS CHECK BALANCE RUN DESIRED?  (YES OR NO)
                                                     YES
```

Fig. 11 Program Printout for the Balancing Demonstration (Cont'd)

```
SET ROTOR SPEED AT      750.0 RPM.

                                                      D
   MIRROR COMMAND PLANE #  1
   PHASE ANGLE DEGREES     33.33
   FIRE COMMAND NUMBER OF SHOTS    127
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
   MIRROR COMMAND PLANE #  5
   PHASE ANGLE DEGREES    168.12
   FIRE COMMAND NUMBER OF SHOTS     80

   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D
STOP ROTOR
CORRECTED ROTOR

  BALANCING SPEED =       6300.0 RPM
                        MEASURED VIBRATION                NET VIBRATION
SENSOR     AVE SPEED    AMPLITUDE        PHASE      AMPLITUDE         PHASE

     1        6292.0        1.3788      101.7819       0.5044       153.5948
     5        6290.2        1.2514      124.8809       0.5088       153.7052

  ARE THESE AMPLITUDES SATISFACTORY
ENTER YES OR NO FOLLOWED BY RETURN       NO

ENTER FILENAME FOR STORING INFLUENCE COEFS.: DK1:[200,200]INFL.DAT
 CORRECTION WEIGHTS  --   SET NO.  1

 TOTAL WEIGHT AT ANGLE
    SHOTS        DEGREES

     82.6          17.34
     92.7         175.65

  CHECK BALANCE RUN
IS CHECK BALANCE RUN DESIRED?  (YES OR NO)    NO

                       PROGRAM RESTART
```

Fig. 11 Program Printout for the Balancing Demonstration (Cont'd)

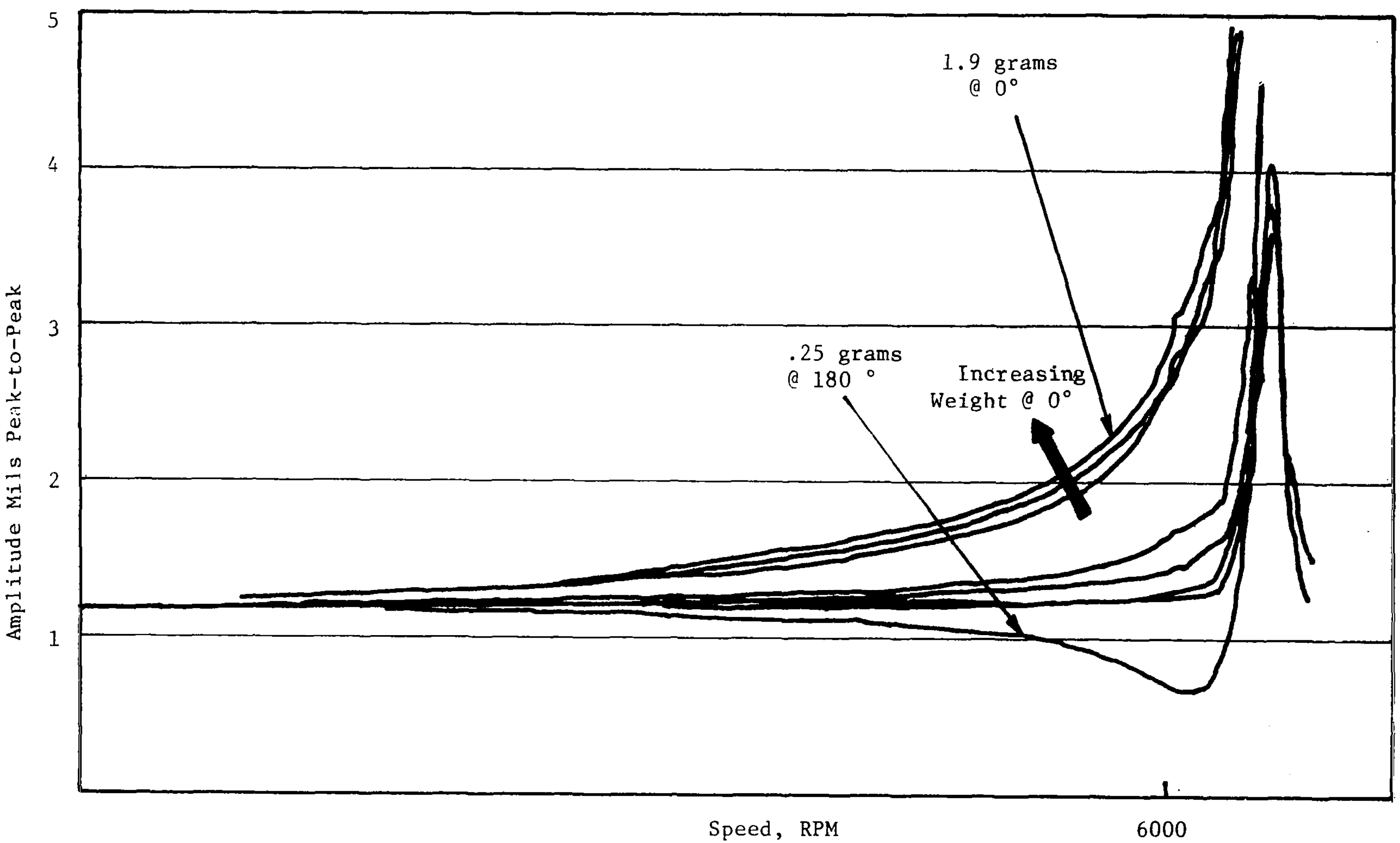



Fig. 12 Effect of Adding Wax Weight to Balanced Rotor Plane 1

Once the uncorrected or runout data was automatically recorded by the balancing program, the rotor was manually decelerated to 750 rpm. This speed was used for the firing of trial weights as listed below. At this speed the efficiency of the laser balancing system was increased because the amount of material removed per shot is much higher than at 6300 rpm.

| Trial Weight | Shots | Angle Degree |
|---|---|---|
| Plane 1 | 60 | 40 |
| Plane 5 | 60 | 200 |

After each trial weight in each plane, the rotor was accelerated to 6300 rpm to obtain the influence coefficients. The balancing program takes the data and automatically accounts for the fact that the trial weights in each previous plane cannot be removed. Correction weights or shots were specified as:

Plane 1 127 shots at 33°
Plane 5 80 shots at 168°

The laser automatically installed these weights (removed metal) at 750 rpm. Figure 13 shows the corrected rotor response and the passing through the critical. The correction in the rotor was as follows:

Uncorrected Net Vibration, 6317 rpm
Plane 1 0.86 mils (peak-to-peak) at 163°
Plane 5 0.98 mils (peak-to-peak) at 160°

Laser Corrected Rotor, 6290 rpm
Plane 1 0.50 mils (peak-to-peak) at 153°
Plane 5 0.50 mils (peak-to-peak) at 153°

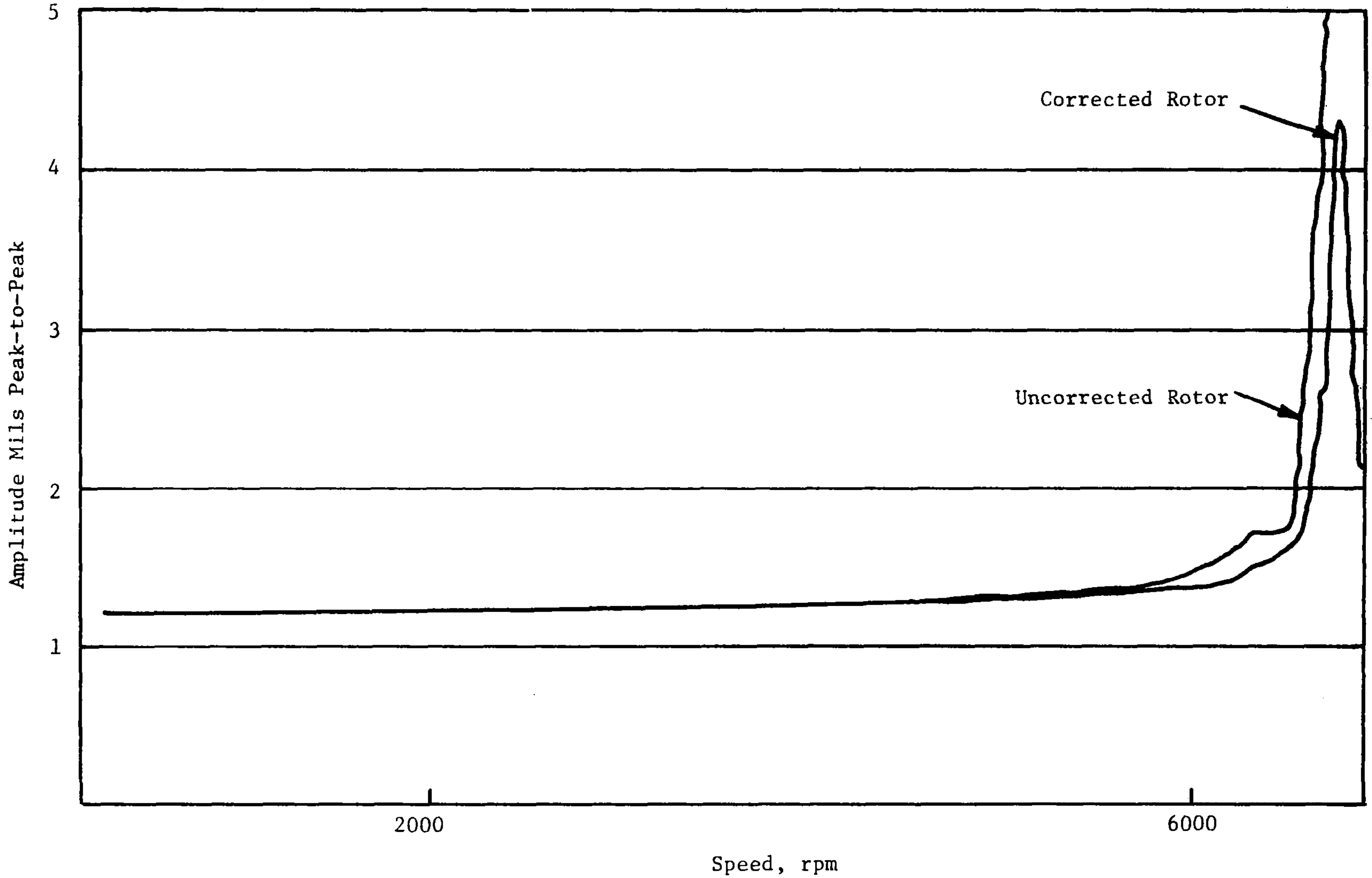



Fig. 13  Effect of Trial Weights and Corrected Rotor Response of Plane 1

# VI. DEMONSTRATION OF MULTIPLE CORRECTION SETS BY LASER

## Introduction to Demonstration

Subsequent to the balancing demonstration of Section V, further developments were made to the laser balancing system to improve the procedure of acquisition and output of data. The existing software did not have the ability to determine the optimum trial weight location. The changes allowed the laser trial weights to be placed in a location or zone where the laser will correct during balancing, since the rotor response was printed after each weight. This decreased the number of shots required to balance the rotor, since the operator would specify trial weights opposite the net rotor response data.

Using software improvements of the system, a demonstration was made of the laser balancing procedure. Two-plane balancing was demonstrated that enabled the rotor to pass through the first critical speed at approximately 6300 rpm. The rotor was initially assembled with an unknown balance. The results indicated that Plane 1 had a large imbalance, as shown by the large number of correction shots required. During this demonstration, uncorrected rotor data was taken, and trial weights for two planes and three sets of correction weights were installed without stopping the rotor.

## Description of Software Improvements

Revision of the laser balancing software included a revision of the calculation and output procedures. The initial rotor data, calibration factors and laser initialization were immediately presented after the data file was defined. After the acquisition of out of roundness and uncorrected rotor data, the results were immediately printed out. From the uncorrected rotor information, the operator could select optimum trial weight locations. Also, a single program could be used for either type of balancing run, using stored influence coefficients, or calculating influence coefficients from trial weights.

## Demonstration

The rotor was assembled with unknown unbalances at each end of the rotor and data was taken of the out of roundness and uncorrected rotor condition. The rotor was accelerated to a maximum speed of 6350 rpm. Due to the probe clearance, the rotor speed was not increased beyond this speed.

Trial weight shots at Plane 1 were taken at 750 rpm of 43 shots at 180 degrees. The rotor was then accelerated to 6300 rpm where the response data was taken. Decelerating to 750 rpm, trial weight shots at Plane 5 were taken of 36 shots at 190 degrees. Response data was again taken at 6300 rpm.

The laser balancing program then calculated a correction weight set of:

<u>Correction Set #1</u>

Plane 1 588 Shots -5.3 Degrees

Plane 5 52 Shots +37.8 Degrees

The laser balancing system then automatically fired the laser for these requirements. Due to the large number of shots required, the number of table movements required was:

$$\frac{\text{SHOTS}}{\text{MAXIN}} = \frac{588}{15} = 40$$

Where: MAXIN = Maximum Number of Indexes

The present indexer increment was set at .040 inches per index.

The required burn zone equals:

40 (.04) = 1.60 inches

Since the sacrificial ring is approximately 1-1/8 inches wide, a quantity of shots were taken with the laser firing off the target zone without removing material. It was decided to continue the balancing procedure anyway, to determine if the system would continue to balance the rotor. This would be a real test of the automated trim balancing procedure.

After the first corrections were applied, the rotor response data was again taken at 6300 rpm and a second set of correction weights was calculated based on the stored influence coefficients previously obtained.

<u>Correction Set #2</u>

Plane 1 345 Shots +0.4 Degrees

Plane 5 33 Shots +33.2 Degrees

After making the corrections, rotor response data was taken at 6300 rpm and the net vibration levels were reduced 52 percent. The rotor was accelerated beyond 6300 and thru the first bending critical speed.

The laser balancing system automated procedure was successful.

A third correction weight set (second trim set) was calculated:

Correction #3

Plane 1 145 Shots +4.5 Degrees

Plane 5 48 Shots +25 Degrees

Again, this set was installed by the laser system which further reduced the vibration levels by 20 percent from the previous rotor response.

Part of the reason for the large number of shots required by Plane 1 is due to a deterioration of the movable mirror 10.6 nanometer wavelength surface coating. Deterioration of this surface is evident by a white spotting or pit marks. In the present configuration, this movable mirror is .5 x .5 inches. The mirrors used in the optics for Plane 5 are of a different design; they have performed satisfactorily with no deterioration.

## RESULTS

The following vibration amplitudes were observed from the demonstration:

| | NET VIBRATION AT 6300 RPM AMPLITUDE (MILS PEAK-TO-PEAK) | |
|---|---|---|
| CONDITION | PROBE 1 PLANE 1 | PROBE 5 PLANE 5 |
| UNCORRECTED ROTOR | 4.10 | 4.00 |
| CORRECTION #1 | 2.28 | 2.10 |
| CORRECTION #2 | 1.10 | .84 |
| CORRECTION #3 | .88 | .82 |

Correction sets #2 and #3 enabled the system to pass thru the 1st critical speed. Figure 14 is the computer output of this demonstration. The response curves

```
 RUN DK1:LASERT
MTI  LASER BALANCING SYSTEM
DATE OF REVISION 5/8/78   REVISION NUMBER 10

 09-MAY-78   18:05:53

 ENTER FILENAME FOR ROTOR SYSTEM SETUP DATA   DK1:[200,200]DATAL.DAT

TRIAL WEIGHT BALANCING METHOD
 NUMBER OF SENSOR READINGS       NR =  2
 NUMBER OF SPEEDS               NSP =  1
 NUMBER OF BALANCING PLANES     M   =  2
 SENSOR NUMBERS USED IN BALANCING      1     5
 PLANE  NUMBERS USED IN BALANCING      1     5

 AMPLITUDE CALIBRATION FACTORS

 SENSOR      MULTIPLY       MULTIPLY        ADD TO
   NO.     AMPLITUDE         PHASE          PHASE
         MILS PER VOLT                      DEGREES

   1        2.8280         1.0000       90.0000
   5        2.8280         1.0000       90.0000

 LASER INITIALIZATION SEQUENCE
   MAXIMUM SHOTS PER INDEX POSITION  MAXSHT=  20
   MAXIMUM NUMBER OF INDEXES         MAXIN =  15
   FIRING OPTION CODE                 FCODE=   0
   FIRING SPEED RPM                   FSPD =   750.0
   FIRING SPEED TOLERANCE RPM        FSPDT =     0.0

DATA ACQUISITION - OUT OF ROUNDNESS

SET ROTOR SPEED AT      2300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D

 OUT OF ROUNDNESS DATA

SENSOR     AVE SPEED     AMPLITUDE        PHASE
              RPM       MILS PK-PK       DEGREES

     1        2306.8        0.6412      119.4556
     5        2302.3        0.8199      105.2111

DATA ACQUISITION - FOR UNCORRECTED ROTOR
```

Fig. 14  Program Output for Multiple Trim Set

```
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D
MEASURED DATA UNCORRECTED ROTOR
                        MEASURED VIBRATION                NET VIBRATION
SENSOR    AVE SPEED    AMPLITUDE         PHASE    AMPLITUDE         PHASE

     1       6278.3       3.7600    356.8779       4.1407      -10.6204
     5       6293.6       3.8329      7.5762       4.0247       -4.0722

DATA FOR TRIAL WEIGHT IN BALANCING PLANE   1

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED    760.5379
  LASER DELAY ANGLE (DEGREES) =    1.544

   MIRROR COMMAND PLANE #   1
   ENTER PHASE ANGLE IN DEGREES    350
   FIRE COMMAND ENTER NUMBER OF SHOTS TO BE TAKEN    60
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

  TRIAL WEIGHT:      60. SHOTS   IN   350.00 DEGREE LOCATION

 09-MAY-78   18:15:20

SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D

DATA FOR TRIAL WEIGHT IN BALANCING PLANE   5

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED    743.7729
  LASER DELAY ANGLE (DEGREES) =    1.510

   MIRROR COMMAND PLANE #   5
   ENTER PHASE ANGLE IN DEGREES    15
   FIRE COMMAND ENTER NUMBER OF SHOTS TO BE TAKEN    50
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

  TRIAL WEIGHT:      50. SHOTS   IN    15.00 DEGREE LOCATION

 09-MAY-78   18:21:32
```

Fig. 14 Program Output for Multiple Trim Set (cont'd)

```
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D

 TRIAL WEIGHT  --         60.0 SHOTS
PLANE NO.  1            350.00 DEGREES
                           MEASURED VIBRATION               NET VIBRATION
 SENSOR     AVE SPEED    AMPLITUDE        PHASE     AMPLITUDE        PHASE

     1        6273.4       3.4432     358.5327        3.8126       99.7630
     5        6285.0       3.4526       9.4893        3.6273       93.5078

 TRIAL WEIGHT  --         50.0 SHOTS
PLANE NO.  5             15.00 DEGREES
                           MEASURED VIBRATION               NET VIBRATION
 SENSOR     AVE SPEED    AMPLITUDE        PHASE     AMPLITUDE        PHASE

     1        6269.4       3.1231     357.3271        3.5065      101.5820
     5        6304.2       3.5686       8.0162        3.7603       94.4765
 CORRECTION WEIGHTS  --   SET NO.  1

 TOTAL WEIGHT AT ANGLE
    SHOTS       DEGREES

     588.5        -5.34
      52.6        37.82

  CHECK BALANCE RUN
IS CHECK BALANCE RUN DESIRED?  (YES OR NO)    YES

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED   784.5721
   MIRROR COMMAND PLANE #   1
   PHASE ANGLE DEGREES     -5.34
   FIRE COMMAND NUMBER OF SHOTS    588
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED   723.4653
   MIRROR COMMAND PLANE #   5
   PHASE ANGLE DEGREES     37.82
   FIRE COMMAND NUMBER OF SHOTS     52
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED      D
STOP ROTOR
CORRECTED ROTOR
```

Fig. 14  Program Output for Multiple Trim Set (cont'd)

```
  BALANCING SPEED =      6300.0 RPM
                         MEASURED VIBRATION                  NET VIBRATION
SENSOR     AVE SPEED    AMPLITUDE          PHASE     AMPLITUDE           PHASE

     1        6304.0       2.0051        12.3893        2.2774         -3.2255
     5        6315.2       2.0801        24.9058        2.1035          2.3119

  ARE THESE AMPLITUDES SATISFACTORY
ENTER YES OR NO FOLLOWED BY RETURN     NO

ENTER FILENAME FOR STORING INFLUENCE COEFS.: DK1:INFL2.DAT
 CORRECTION WEIGHTS  --  SET NO.  1

 TOTAL WEIGHT AT ANGLE
    SHOTS      DEGREES

     345.0         0.39
      66.9        33.15

  CHECK BALANCE RUN
IS CHECK BALANCE RUN DESIRED?  (YES OR NO)   YES

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED   762.9823
   MIRROR COMMAND PLANE #  1
   PHASE ANGLE DEGREES     0.39
   FIRE COMMAND NUMBER OF SHOTS   345
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED   737.4162
   MIRROR COMMAND PLANE #  5
   PHASE ANGLE DEGREES     33.15
   FIRE COMMAND NUMBER OF SHOTS    66
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0
SET ROTOR SPEED AT      6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D
STOP ROTOR
CORRECTED ROTOR
```

Fig. 14 Program Output for Multiple Trim Set (cont'd)

```
  BALANCING SPEED =      6300.0 RPM
                         MEASURED VIBRATION                NET VIBRATION
SENSOR     AVE SPEED    AMPLITUDE          PHASE     AMPLITUDE            PHASE

     1         6289.0       0.9802        36.5529        1.1030            1.3212
     5         6293.0       1.1143        56.3982        0.8430            9.3517

  ARE THESE AMPLITUDES SATISFACTORY
ENTER YES OR NO FOLLOWED BY RETURN      NO
 CORRECTION WEIGHTS  --  SET NO.  1

 TOTAL WEIGHT AT ANGLE
    SHOTS      DEGREES

     145.8        4.56
      48.3       25.03

  CHECK BALANCE RUN
IS CHECK BALANCE RUN DESIRED?  (YES OR NO)   YES

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED    779.6571
   MIRROR COMMAND PLANE #   1
   PHASE ANGLE DEGREES      4.56
   FIRE COMMAND NUMBER OF SHOTS    145
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0

SET ROTOR SPEED AT      750.0 RPM.
TYPE D AND C.R. WHEN ROTOR IS UP TO SPEED D
SPEED    753.6000
   MIRROR COMMAND PLANE #   5
   PHASE ANGLE DEGREES     25.03
   FIRE COMMAND NUMBER OF SHOTS     48
   LOCATION OF TABLE WITH RESPECT TO CENTER OF DISK = ,     0
SET ROTOR SPEED AT     6300.0 RPM
ENTER D FOLLOWED BY RETURN WHEN ROTOR IS UP TO SPEED     D
STOP ROTOR
CORRECTED ROTOR

  BALANCING SPEED =      6300.0 RPM
                         MEASURED VIBRATION                NET VIBRATION
SENSOR     AVE SPEED    AMPLITUDE          PHASE     AMPLITUDE            PHASE

     1         6300.7       0.7841        43.9226        0.8802           -0.9374
     5         6341.8       1.0649        55.4081        0.8241            5.9526

  ARE THESE AMPLITUDES SATISFACTORY
ENTER YES OR NO FOLLOWED BY RETURN      YES
       LASER POWER OFF
TT6  --  STOP
>
```

Fig. 14  Program Output for Multiple Trim Set (cont'd)

which follow were plotted and are shown in Figure 15. Since the maximum clearance of the capacitance probes is approximately 6-8 mils, an attempt to pass thru the critical was not made for correction Set #1. The composite response of the rotor during initial conditions and after each correction is shown in Figure 15.

## Efficiency of Laser Method

Since the laser module that was used in this demonstration had a recharge cycle of 2 seconds, the firing of 588 shots was approximately 20 minutes for Plane 1. This time is comparable to an operator stopping the rotor, grinding and weighing correction material, and installing weights in the test rotor. Since 36 holes are available at the 5.25 inch diameter of the rotor, typically two correction set screws were required at each plane. A 50-70 percent reduction in vibration levels is typical for both hand grinding and laser methods. An estimate of man-hour savings of the laser technique of balancing is difficult, since this demonstration system was not designed for a production environment. The time savings would be a function of the energy delivered by the laser, and the amount of material to remove. Adding multiple laser modules to each plane and eliminating the movable mirror assembly would halve the balancing time. For manufacturing environments, however, the laser metal removal procedure should be considered when the average amount of metal to be removed from each correction plane is 5 grams or less. An economic analysis considering an initial cost-versus-increased-production rate should be performed.

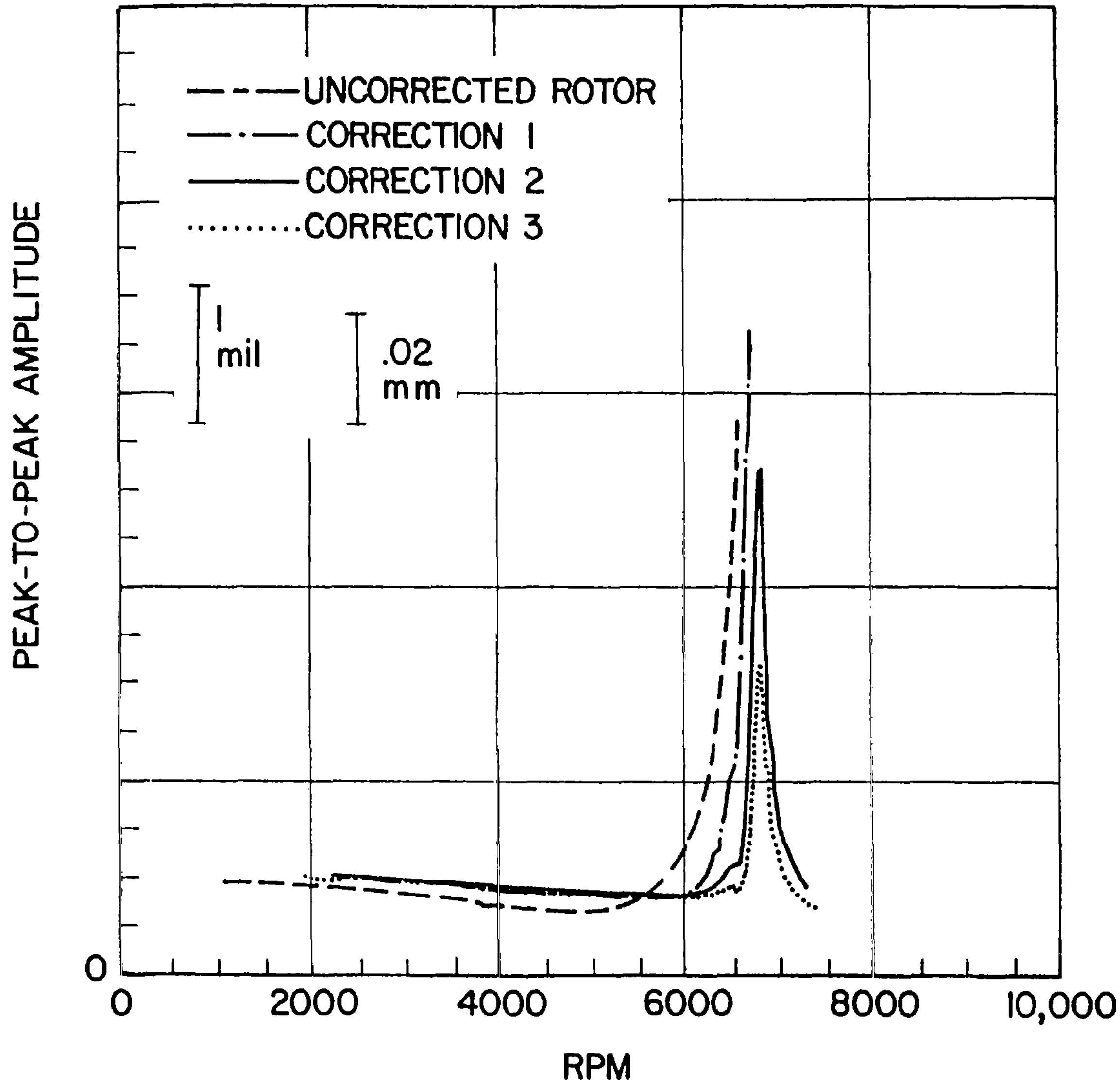



Fig. 15 Response of the Test Rotor During the Laser Balancing Demonstration

## VII. CONCLUSIONS

1. A laser metal removal procedure can successfully balance rotating shaft systems by use of a computer control system.

2. The accurate control of the angular and axial position of the material removal zone can be demonstrated by the system described in this report. Compensation for electronic circuit delay times can be corrected by the computer.

3. The material removal rates are at the low end of those required for production type high speed machinery. However, as the current level of high power laser development efforts continues, increases in removal rates can be expected.

4. The present energy levels of the laser material removal balancing system require that the surface speed be limited to 2,000 feet per second. This limit can also be anticipated to increase as laser development efforts continue.

## VIII. RECOMMENDATIONS

1. The principle area not evaluated within the scope of this contract is the metallurgical effect the laser has on the material removal zone. In future efforts, a metallurgical study should be performed which will investigate fatigue properties, fracture mechanics and grain properties of the material adjacent to the balancing removal zones. This will assist the designer in evaluating the applicability of the laser balancing process and provide the proper material removal zone for laser balancing.

2. This demonstration showed the feasibility of using the laser material removal process for high speed rotating equipment. An effort to optimize the laser configuration, optics, and laser energy levels should be continued to improve the amount of material removed by this process. A mathematic and thermodynamic study of the removal process and removal rates should be completed in order to further optimize this system for production applications.

3. Further experimental data must be obtained to determine the energy delivered by the laser per shot. During some of the static testing variation in the energy per pulse was observed by visual inspection of the drilled holes. The cause of this phenomenon was partially attributed to an out of specification power supply high voltage of the laser system. For long periods of repeated laser firings some change in the beam divergence occurs due to heat of the laser rod at maximum power levels. This may result in variations in the quantity of material removed.

   The addition of an energy output measuring device from the laser and measurement of the beam energy would be an additional aid to determine repeatability of the system.

4. Increasing removal rates should be attempted by adding multiple laser modules and power supplies. In effect, this will increase the total energy available for material removal and increase the potential industrial applications.

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15. Supplementary Notes

Final report. Project Manager, David P. Fleming, Fluid System Components Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

This report describes the modification of a flexible rotor system for two-plane laser balancing. Experimental testing of the laser material removal method for balancing through the first bending critical speed was demonstrated. The test rig, optical configuration, and a neodymium glass laser system were assembled and calibrated for static and rotating material removal rates. The laser control computer program was combined with the influence coefficient balancing process, resulting in a completely automated data acquisition, laser, and balancing system. The laser system rotor was balanced through the first bending critical speed using the laser material removal procedure to apply trial weights and correction weights without stopping the rotor.

17. Key Words (Suggested by Author(s))
Balancing, Flexible rotor balancing, Computer controlled balancing, Laser machining

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