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Improved Jet Engine Maintenance Through Automated Vibration Diagnostic Systems

R. A. Rio
Mechanical Technology Inc.,
Latham, N.Y.

The rapidly increasing cost of maintenance, the demand for increased equipment utilization, fuel costs, and the difficulty of correctly diagnosing internal mechanical problems in fully assembled jet engines, have stressed the need for more effective engine test equipment. This paper describes the successful application of both a component (module) high-speed balancing technique and an Automated Vibration Diagnostic System (AVID) in the U.S. Air Force's high-volume engine overhaul center at Tinker Air Force Base, Oklahoma. the AVID concept to automate troubleshooting procedures for fully assembled rebuilt engines is addressed. This system extracts high frequency vibration data from existing standard instrumentation, thereby providing meaningful mechanical information. A growing appreciation on the part of engine overhaul personnel of the power of automated test equipment has enabled these key features to be combined to reduce operating expenses at engine rebuild facilities.

INTRODUCTION

Significant concern has been expressed in recent years about the relatively high and growing levels of maintenance costs required to keep many kinds of key equipment operational. The aircraft gas turbine engine has been no exception to this trend. Aircraft gas turbine engines have compiled remarkable endurance and safety records over the years, especially given the sophistication of their designs and the rotor speed involved. These records have been and are being earned through expensive and painstaking overhaul practices, applied at regular intervals of operating time. While the costs of this approach have been substantial, the consequences of failure have always far outweighed them. While safety of flight cannot be compromised, future improvements in maintenance engineering can and must be realized to keep the costs of safe operation from becoming prohibitive.

This paper presents two vibration diagnostic techniques which have been developed for the latest jet engine overhaul techniques being developed by the military. These maintenance procedures take advantage of the latest modular jet engine design concepts.

There are two tiers of maintenance decisions. In the first tier, repair decisions will be performed by the end users at the base installations. Engine components or modules will be returned to the depot for repair and/or refurbishment based upon modifications observed by the user or based upon the established time and cycle limit of that particular module in service. The second tier involves removal of entire engines which are then returned for depot level maintenance. Therefore, both complete engines and discrete engine modules will be cycled through the maintenance facilities.

It will be necessary to have a vibration acceptance test which will certify that repaired engines and modules are acceptable for fleet used. As presented here, a high-speed balancing system will identify potential problems before the module is shipped to the field. For entire engines which require a complete test cell acceptance procedure, an Automated Vibration Diagnostic System (AVID) has been developed which will identify internal mechanical faults using the standard engine vibration sensors.

TECHNICAL DISCUSSION

High Speed Balancing

Rotor balancing is the process of applying a single set of correction weights simultaneously in two or more planes on a rotating shaft to achieve low vibration levels at each measurement location along the shaft, and at a special number of shaft speeds. In its simplest form, this process involves two planes, two sensors, and a single, relatively low speed. In its most complex form, as many as eight or ten balancing planes may be involved, together with an equal number of sensors. As many as six or eight balancing speeds may be required.

When a rotating body remains rigid (i.e., no elastic axis bending, over its entire operating speed range), the simplest, two-plane, low-speed approach can be fully satisfactory. It is this fact which has permitted the governing relationships to be "programmed" in electronic packages as parts of commercially offered balancing machines. What causes difficulty in many cases is the fact that the commercial balancing machine fails to simulate adequately the design operating condition of the component.

The balancing of advanced rotating systems is becoming increasingly difficult with design trends toward lighter, more flexible components which turn at higher speeds. The operating speeds of many systems now being designed are often beyond the first

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critical. The reason this situation causes concern is that the modes of vibration at the critical speeds often involve significant bending of the system's elastic axis. Since these deformation properties are speed dependent, low-speed two-plane balancing has only limited effectiveness. In fact, such balancing can often make vibration levels worse at the bending critical speeds.

Unfortunately, present-day manufacturing procedures, in spite of their high-precision nature, leave some distributed residual unbalance in each rotating component. The result is a considerable trial-and-error effort to find a satisfactory balance at the trim-balance stage, and increased efforts toward tighter tolerances and more stringent assembly procedures; all of which can be very costly. As rotors become longer and more flexible, and as lighter weight rotor systems are developed, balancing requirements and methodology must adjust to accommodate them. Problems introduced by disassembly and reassembly are also significant; especially in a gas turbine engine having several disk and blade assemblies, bearings, and a cantilevered turbine.

A procedure for performing rotor balancing in two or more planes, so as to achieve low vibration levels at each of a number of measurement locations and at each of a number of speeds, has been developed. The procedure is conceptually quite simple, and has been designed for operation by technician-level personnel. It may merely be used to supplement the capabilities of a commercially offered balancing machine; or, in its most complete form, it offers the option of replacing a series of two-plane balancing steps by a single multiplane-multispeed balancing of the rotor in its final installation.

In their maintenance philosophy, the military has identified a number of potential advantages in high-speed balancing gas turbine modules.

<u>Cost Savings.</u> It is often extremely complex, time consuming and expensive to high-speed balance an engine while it is installed in a test cell. Quality high-speed balancing of components will often reduce or completely eliminate the need for assembled engine balancing and reduce the rejection rate; thereby saving teardown, reassembly and retest cost.

<u>Improved Rotor Life.</u> If the engine component is flexible (i.e., approaches or traverses bending critical speeds within its operating speed range), high-speed balancing offers unique advantages because of the inability of traditional low-speed balancing to reduce shaft vibrations at these speeds.

<u>Component Diagnostics.</u> Operating component parts at high speeds before assembly to the engine allows a significant degree of component diagnostics (i.e., shift in parts, misalignment, faulty bearings, etc.). This, therefore, occurs before the added cost and complexity of installing a complete engine for test and trim balancing.

<u>Accessibility to Problem Component.</u> It is often impractical or impossible to access rotors inside an assembled engine. Accessiblility to prescribed balance planes is also often limited because of the "trapped rotor" design of many gas turbine engines. Component "stack up" also makes access to interior shaft components impractical in the assembled engine, but practical in a high-speed balancing module.

<u>Seating of Sub-Component Parts.</u> Operating a component before assembly into the engine allows sub-component parts (i.e., turbine blades, snap fits, etc.), by the action of centrifugal force, to seat in the position in which they will run in an engine. This is especially important in shafts with a high degreee of sensitivity to changes in unbalance. Such "run in" of component parts cannot be achieved by only low-speed operation.

<u>Application to United States Army Jet</u> Engines

A system developed for the United States Army permits high-speed balancing of assembled power turbine shafts for both T53 and T55 helicopter engines. Based on an extensive background study, it was determined that one of the power turbines (T53) traverses a bending critical speed well below its normal operating speed in the engine. The other power turbine (T55) traverses a rigid body critical speed and approaches its first bending critical speed at its normal operating speed.

In their present configuration, neither of these engines have the capability to trim balance the power turbine shaft in the test cell. Each vibration-related reject in the test cell requires engine removal and tear down for subcomponent balancing. The engine must then be rebuilt, reinstalled, and rerun in the test cell. The prototype high-speed balancing system allows both T53 and T55 power turbine shafts to be run and high-speed balanced as an assembly before installation into the engine.

Figure 1 shows the major mechanical components of the balancing system. Drive power is provided by a variable-speed electric motor. Speed is increased through a gearbox with output shaft speeds equal to engine operating speeds for the power turbine shaft. The shaft is operated in a vacuum chamber to both reduce the windage (and therefore the amount of drive power required), and to provide for operator safety.

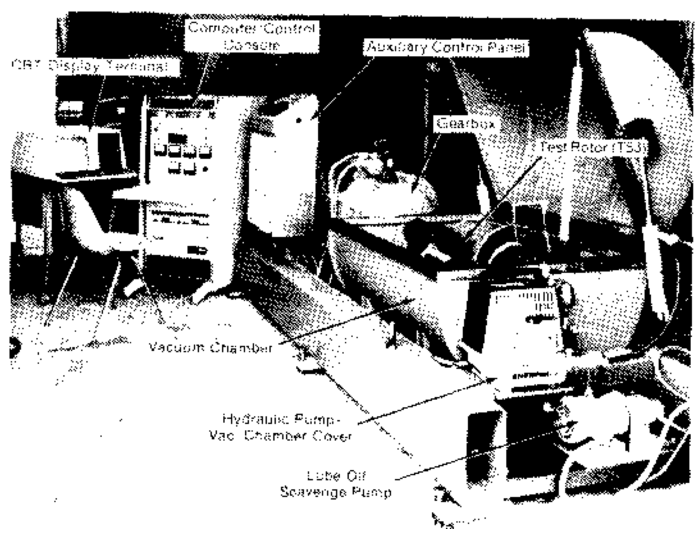

Fig. 1 Prototype high-speed balancing system for U.S. Army helicopter engines

A control console with dedicated minicomputer and CRT terminal is located in a separate control room. An auxiliary control panel mounted on the test stand provides for local low-speed operation and control.

In order to duplicate the dynamic characteristics of the engine installation, engine bearings support structures are used to mount the shaft for balancing. Displacement probes are used to measure shaft deflection. Vibration data are routed to the minicomputer for automatic data acquisition and balancing weight calculation.

Figures 2 and 3 show typical results for high-speed balancing T53 and T55 power turbines using the prototype high-speed balancing system.

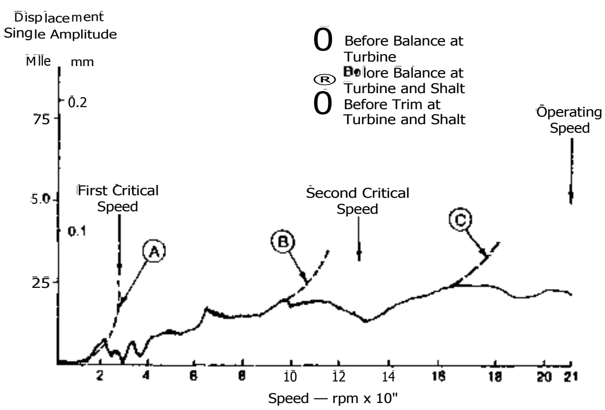

Fig. 2 Results of high-speed balancing T53 power turbine

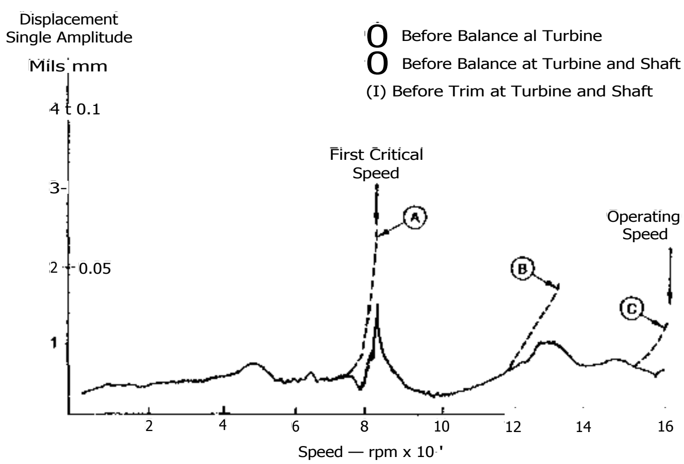

Fig. 3 Results of high-speed balancing T55 power turbine

Automated Vibration Diagnostics

In several cases, operators of gas turbine engines have begun to adopt the practice of "on-condition maintenance to reduce costs. In the process of this change, the increased emphasis that must be placed on diagnostic systems and procedures has become apparent. These procedures are required to obtain data to determine the presence of a problem, identify trends, and locate the specific faulty component within a fully assembled engine.

Significant technological advances have occurred in recent years in small low-cost minicomputers, digital data processing and filtering, and new methods for using high-frequency vibrations as information carriers. These advances are expected to be of great utility for new monitoring and diagnostic procedures.

The first level of analysis is a comparison of the output signal levels of instrumentation with predetermined limits, such as bearing vibration. The comparison is accomplished by analyzing a number of past readings and permits an initial classification of the machine's condition, such as whether the equipment is operating within safe limits, or whether a large percentage change has occurred in any measured parameter since the last measurement. Presenting this data as a function of time can indicate wear, growing unbalance or component degradation.

Once a signal has been found to be out of bounds, a detailed analysis of the signal and related parameters is initiated. High-speed detailed sampling provides a full-frequency component analysis of vibration. Oil pressure and temperature, and other key static signals are sampled concurrently. This information, together with the operator's understanding of the machinery, will often permit the operator to make a reasonably accurate determination of the probable cause of the observed variance. Typical actions the operator may wish to have the system undertake at this point may include: providing an advisory to maintenance personnel to inspect for obvious unusual circumstances or operating levels; increasing the frequency at which the review of the machine occurs; trending and analyzing measured machine responses for representative past operating history; calculating full-frequency component composition of time-varying signals to identify specific contributing frequencies and amplitudes; and comparing frequency components with stored tables of potential forcing frequencies, such as one-per-rev, gear mesh, etc. The structure of the diagnostic system's logic often permits the maintenance engineering staff to tailor the system to their particular needs.

Analytical and experimental information about the machine may be stored within the system. For example, design data about blading, bearing design, coupling characteristics, critical speeds, and sometimes even analytical equations may be provided. With such information, automated diagnosis is possible. When a machine is overhauled or undergoes maintenance, the details of any observations can be entered into the data base, and the system can categorize experienced changes in behavior with actual physical parameters. Theoretical considerations may be reinforced through operating experience and successful maintenance actions.

As time elapses, the data base assembled through these interactions permits more accurate diagnostic logic to be prepared. The important concept in the logic is that the system learns from proven experience and can formally document machine problem histories. Predictive maintenance recommendations are also available. Machinery operating costs can be minimized by providing cost-based logic for accomplishing specific maintenance on only those modules requiring checking. The symptom-fault logic may be asked to identify preventive actions and replacement parts as part of the overhaul process.

Application to United States Air Force Jet Engines

The technologies discussed above have been successfully combined to provide an Automated Vibration Diagnosis System (AVID) for United States Air Force jet engines. The system was installed in four engine test cells at one of the main United States Air Force engine overhaul centers, Oklahoma City Air Logistics Center (OC-ALC). Operation of the equipment by Air Force personnel has demonstrated the practical application of combining minicomputer technology with gas turbine engineering expertise to provide the Air Force with a system which provides fuel savings, increased engine production capacity, and greatly reduced vibration rejection rates.

Overhaul Procedures. Overhaul procedures require that rotating components undergo both static and dynamic balancing during the overhaul process. Engine parts are first weighed and balanced as individual parts, then balanced as assemblies (i.e., compressors and turbines) prior to final assembly. Following final assembly, engines undergo an acceptance test during which critical performance and operating parameters are determined.

During the acceptance test, engines frequently experience vibrations which exceed allowable technical order limits. Depending upon the amplitude, frequency, and location of the vibrations, an engine may be trim balanced while it is on test. If trim balancing is not possible (e.g., vibration not synchronous with rotor vibration, or indicated trim weight too large), then the engine is returned to the final assembly area for corrective rework. Former engine technical order procedures required that three trial trim balance weights be installed separately and the engine operated after insertion of each weight. Data resulting from each run was used to calculate the amount and location of a final balance weight. Approximately eight hours were required to trim balance an engine using this procedure. One major objective of the diagnostic system was to reduce the excessive amount of time required to trim balance the engines.

Engines on which trim balancing was not permissible were returned to the final assembly area with only minimal vibration data available to direct engine rework. Information provided was highly subjective and dependent on test cell operator experience. As a result, rework which was performed on an engine often did not correct the problem, causing the engine to be rejected several times due to excessive vibration levels. Repetitive rework to correct vibration problems results in additional costs, much of which could be avoided if accurate repair action recommendations were available. Such recommendations were another major objective of the diagnostic system.

Engine rework and test costs are expected to continue to increase as a result of upward trends in manpower and material costs. In addition, the complexity of the new generation of turbofan engines is also resulting in increased maintenance time and costs. These factors, coupled with the requirement for rapid turnaround of engines undergoing overhaul (due to reduced engine inventories) required that a diagnostic system be available to reduce the time required to trim balance, test and provide accurate diagnostic information to direct engine rework.

Automated Engine Trim Balancing Benefits

The TF30 engine was selected for the pilot system demonstration because it is designed for trim balancing and was considered by the Air Force to be a typical engine in its maintenance requirements and vibration characteristics. The engine vibration signals used during acceptance testing were derived from the three standard military velocity sensors normally installed on the engine during test. Before filtering within the vibration amplifier, the signals are routed, along with the speed measurements, to the computer room (see Figure 4).

The TF30 engine AVID System (see Figure 5) consists of six assemblies; the central balancing system, four digital signal processors, and a CRT terminal and hardcopy unit. All of these assemblies are located in a central computer room adjacent to the four test cell control rooms. Each of the digital signal processors is dedicated to monitoring speed and engine vibration signals from one test cell. All the digital signal processors are connected to the central balancing and diagnostic system. The CRT terminal and hardcopy unit

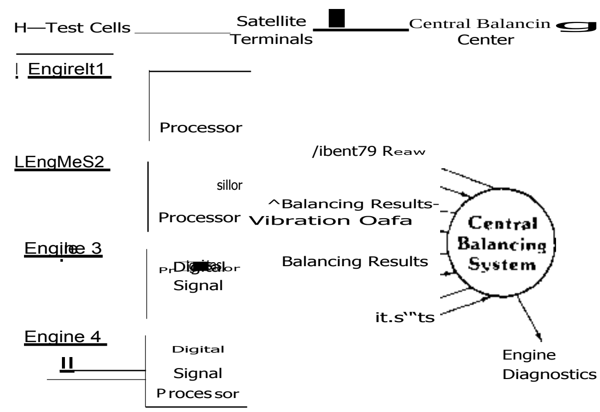

Fig. 4 Schematic of an Engine Trim Balancing and Diagnostic System

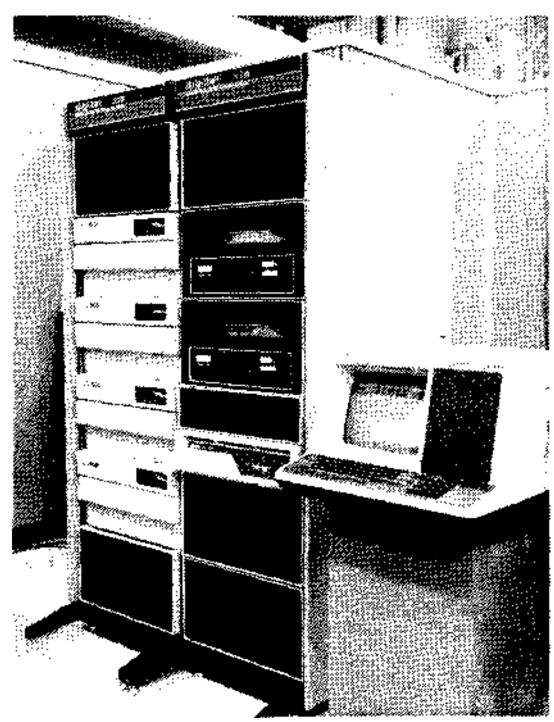

Fig. 5 TF30 Engine AVID System

are connected to the central balancing system or the digital signal processors. During acceptance testing, the trim balancing system is activated if the engine vibration exceeds the technical order limit. Vibration data is automatically acquired and processed to provide a spectral analysis of the overall signals of the engine's vibration sensors.

The size and location of the required trim balance weight are calculated by the system based on the engine's vibration characteristics. The unique aspect of the trim balancing portion of the AVID system is that trial weight runs are not needed. Engine sensitivity data, also known as influence coefficients, are stored within the minicomputer system. These data are then recalled and processed with the dynamic response of the engine on test to calculate the proper correction weights.

During a verification test period, ten TF30 engines were trim balanced. Trim balancing was successful in all cases. The engines were trim balanced using the influence coefficient method and the engine vibrations were reduced to a level below the technical order specifications. Engines are now routinely trim balanced by Air Force maintenance personnel. The average time to trim balance has been reduced to 1 hour and 20 minutes, compared to the original 8 hours. Test cell time per engine was thus reduced by about 80% for the trim balancing operation, with attendant savings in fuel usage and increases in engine production rates.

Automated Engine Condition Diagnosis Benefits

The key principles of the vibrations diagnostic system operation are based on engineering experience in machinery dynamics. This experience has shown that dynamic observation, particularly of rotor and casing vibrations, is an excellent method to identify existing or impending problems. The complex raw signal data can be processed to provide reliable information that permits the evaluation and pinpointing of the problem source. These diagnostic elements have been combined into systems for making accurate decisions once suitable levels of vibrational characteristics have been defined. The AVID system minimizes the decisions required of the operator and offers rapid identification of problems. The system samples the outputs of the standard existing engine vibration sensors in a logical sequential manner to arrive at a decision as to the condition of the engine under test.

The engine condition diagnosis system acquires both synchronous and nonsynchronous vibration signatures from engines in all four test cells. The system conducts an analysis of each engine's vibration response and produces a hardcopy printout indicating the cause for high vibration, numerically ranked from highest to lowest severity. The TF30 engine Sympton-Fault Matrix, based upon existing data and upon preprogrammed engineering knowledge of the engine, identifies the engine faults. Malfunctions are identified in the order of severity. This unique system feature makes use of general symptom-fault relationships for gas turbines, with specific experience probabilities for the TF30 engine. The diagnostic printouts indicate those faults which should be corrected. These data provide guidelines to the maintenance staff and help establish rework priorities.

Vibration diagnostics were performed on ten TF30 engines during a verification test period. To document the accuracy of the predicted engine faults, maintenance action worksheets accompanied the engines that were rejected for vibration-related malfunctions. Successful correlation between the AVID System's diagnostic summaries and the actual maintenance required by the engines has provided verification of the TF30 vibration diagnostics. The verification test included TF30-P7, TF30-P9, and TF30-P100 engines. The diagnostic system proved nearly 90% accurate (20 out of 23 cases).

In addition, the system maintains an archive of engine data:

- Stored signatures of rejected analysis
- Stored signatures of average engines
  - Overall vibration
  - Ni and N2 components versus speed
  - Spectral plots
  - Six-month sampling (continuously updated)
- Engine serial numbers tracked for short term
  - Repeat rejects identified
  - Engine corrective maintenance history compiled
- Six-month interval of good engine data
  - Overall vibration
  - N1 and N2 components versus speed
  - Retrieval data on earlier rejects

Automated Engine Performance Diagnosis Benefits

In addition to vibration-related engine rejections, a significant portion of post-overhaul rejections are caused by gas-path performance problems such as low thrust, high exhaust gas temperature and high specific fuel consumption. A methodology is being developed [Ref. 1] to increase the acceptance rate of overhauled J75-P-17 turbojet engines. To avoid engine modification, a minimum number of additional sensors were installed to diagnose faulty components from the performance signature. A computer simulation was also developed to identify the faults and to calculate the beneficial effects of easily installed changes or replacements of components. Gas-path performance diagnosis is planned for implementation on the installed AVID system. Static channels such as those for pressure and temperature will be incorporated into the symptom-fault logic to expand the system capability.

SUMMARY AND CONCLUSIONS

Automated systems for balancing and diagnosing engine faults has been designed, developed, and successfully demonstrated in production jet engine overhaul facilities.

Quality high-speed balancing of components will often reduce or completely eliminate the need for assembled engine balancing and reduce the reject rate, thereby saving teardown, reassembly, and retest costs.

Stored engine sensitivity data can be used to calculate single-shot balance weights which, when installed, bring the engine vibration down to acceptable levels. This process has eliminated the need for trial weights and average trim balance time has been reduced from between 7 and 8 hours to 1 hour and 20 minutes through the use of this system.

An automated diagnostic system which uses only vibration data from standard sensors has successfully predicted faults within the engine. During a verification of the system's diagnostic capability, nine engines were torn down and inspected with 90% accuracy of predicted engine faults.

Based upon fuel savings, increased engine production capacity, and reduced vibration reject rate, the installed trim balancing and diagnostic system is projected to yield a multimillion dollar cost savings in its first year of operation.

Air Force maintenance personnel are routinely operating the trim balancing and diagnostic system without additional skilled personnel during normal engine acceptance testing.

The demonstrated system can be expanded to include gas-path performance diagnostics, and with field-level communication and data processing, should provide a practical method of engine health accountability during the entire life of the engine.

REFERENCE

1. Lazalier, G.R., Reynolds, E.C., Jr., Jacox, J.O., "A Gas-Path Performance Diagnostic System to Reduce J75-P-17 Engine Overhaul Costs," ASME, 1978, Paper No. 78-GT-116.