Quality Control Systems For Jet Engine Balancing

Michael Schonfeld
Senior Applications Engineer

Air Transportation Industry
The air transportation industry is a global business whose roots have spread from traditional technology centers to what were once third world countries. Due to the diversity of cultures impacted by this growth, it has become a necessity to establish practices and standards applicable to maintenance and overhaul, particularly rotating components which experience high stresses in operation. As a result, the International Organization for Standardization (ISO), Society of Automotive Engineers (SAE), and other organizations have developed quality practices pertaining to the balancing of rotating components.

Balancing Criteria and Concerns
Safety issues arising from inherent risks associated with air transportation technology have caused these organizations to focus upon techniques and practices for reducing risk and ensuring the final balance, or rather unbalance, quality of a component. The International Organization for Standardization published ISO 1940/1 to assist component designers and manufacturers in determination of permissible residual unbalance of rigid rotors. General categories of representative rigid rotors, referred to as "Quality Grades," were established as guidelines in ISO 1940/1.

Quality grade represents the circumferential velocity of the center of gravity, and is defined as the product of the permissible eccentricity (millimeters) and the frequency of rotation (radians per second), reference Equations 1 through 3; its unit of measure is therefore millimeters per second.

1. **G=e(^)**
   Where G is the quality grade in mm/s, e is the eccentricity in mm, and (^) is the frequency of rotation in rad/s.
2. **e=U/W**
   Where E is the eccentricity in mm, U is the total unbalance in g-mm, and W is the mass of the rotor in grams.
3. **(^)=(2ϖN)/60**
   Where (^) is the frequency of rotation in rad/s, and N is the rotational speed in revolutions per minute.

For example, assume a high pressure turbine stage weighs 70 lbs., and the maintenance and overhaul manual calls for .2 oz. in. of residual unbalance following dynamic balancing in a horizontal balancing machine. The manual requires a minimum balancing speed of 900 rpm. Service speed is 6000 rpm.
e=U/W, where:

U = (0.2oz in. / 16 oz. per lb.) x 454 grams per lb. x (25.4 mm per 1 in.),
U = 144 g-mm
and where W = 70 lbs. x 454 grams per lb. mass = 31,780 grams.
e = (144 g-mm)/31,780 grams.
e = .0045mm
(^)=(2ϖN)/60, where N = 6,000 rpm
(^)=(2ϖ6000)/60
(^)=628 Radians per Second
G=e(^)
G=(.0045mm)(628 Radians per Second)
G=2.83 mm/sec.

Therefore, the high pressure turbine stage will be balanced to a quality grade of G2.83. This example is for illustrative purposes only. Usually, the unbalance tolerance per plane is derived directly from ISO 1940, quality grade G2.5 or G6.3.

Depending on the application, assembled aircraft gas turbine rotors, gas turbines, and similar components are typically balanced to a quality grade from G2.5 to G6.3. Since the majority of jet engine rotors are not perfectly rigid structures at their service speeds, and balancing tooling is necessary to facilitate the balancing process, these quality grades can serve only as guidelines for the tool design engineer.

The tool design engineer must be cognizant of both safety limits and practical limitations imposed by rotor, balancing tooling, and balancing machine designs. This relieves the burden of responsibility for establishing balancing quality standards from the overhaul and maintenance facility. The overhaul and maintenance community is however, responsible for procuring and establishing the correct balancing tooling, balancing machine, and balancing practices necessary to achieve minimum residual unbalances dictated by jet engine manufacturers.

Standard Practices and Procedures

Because of the flexibility of jet engine rotors, established practices require jet engine rotors to be statically balanced as individual rotor stages, and then dynamically balanced as multi-stage rotor modules. This process serves to reduce internal bending moments caused by the unbalance of individual rotor stages. Vertical balancing machines are commonly used for static balancing of individual stages, while horizontal balancing machines are employed for dynamic balancing of multi-stage rotor modules. Balancing quality is dependent upon three issues, the capability of the balancing machine, the configuration of the rotor, and the design of the tooling. Should one fail to achieve the minimum residual unbalance of an individual rotor stage for whatever reason during static balancing, a cascade or “domino” effect in the form of unacceptable residual unbalance may plague the rotor module containing this rotor stage during dynamic balancing. An event such as described will often task cost containment and flight safety efforts, which necessitates the establishment of quality control systems for balancing of jet engine rotor modules and stages.

There are three processes available to the overhaul and maintenance facility for ensuring the effectiveness of such a quality control system: Balancing Machine Performance Testing, Tooling Audit and Control, and Rotor Quality Monitoring. Collectively, balancing machine performance testing, tooling audit and control, and rotor quality monitoring can offer an effective balancing quality control system.

Balancing Machine Performance Testing

Balancing machine performance testing is employed for confirming the capability of the balancing machine to meet the challenges of the balancing task. SAE International has established Aerospace Recommended Practices (ARPs) for configuration, operating practices, and performance testing of balancing machines employed for balancing jet engine components. SAE ARP 4048 addresses horizontal balancing machines while SAE ARP 4050 addresses vertical balancing machines. SAE ARP 4162 concerns proving rotors for both horizontal and vertical balancing machines.

Balancing machine performance testing provides the documentation necessary to prove the operational status of a balancing machine. Testing ensures the balancing machine meets the requirements necessary to balance jet engine components and modules. Proving rotors in accordance with SAE ARP 4162 are employed to conduct balancing machine performance tests. With proving rotors and test masses certified to the National Institute of Standards and Technology (NIST), periodic performance tests demonstrate compliance with performance standards, which are established and traceable. This process is fundamental to the establishment of a quality monitoring and control program for balancing machines.

Performance testing can assist in troubleshooting difficult balancing tasks which employ complex tooling and rotor configurations. By determining a balancing machine meets its performance specifications following the SAE test, greater attention can be focused upon other elements comprising a balancing setup such as tooling, the tooling to rotor interface, or the rotor itself.

Proving rotors in accordance with ARP 4162 are available for five classes of horizontal balancing machines and six classes of vertical balancing machines.Table 1 lists the applicable machine classes and rotor sizes required to conform with ARP 4048, ARP 4050, and ARP 4162. Figures 1 and 2 show results from a typical performance test with a properly functioning balancing machine.

Table 1
SAE ARP 4162 Proving Rotors for
Horizontal and Vertical Balancing Machines

Machine Type	Rotor Weight (lbs.)	Machine Class	Schenck Equivalent Machine
Horizontal	11	30	HL1
	50	100	HL2
	50	300	HF3, HF4, HL4
	150	1000	H40, HF5, HL5
	500	3000	HF50, HL50, HL6
Vertical	8	25	V1L
	25	50	V2L
	25	100	V3L
	80	250	V4L
	250	500	V40L
	250	1000	V5L

End drive test for clockwise direction of rotation

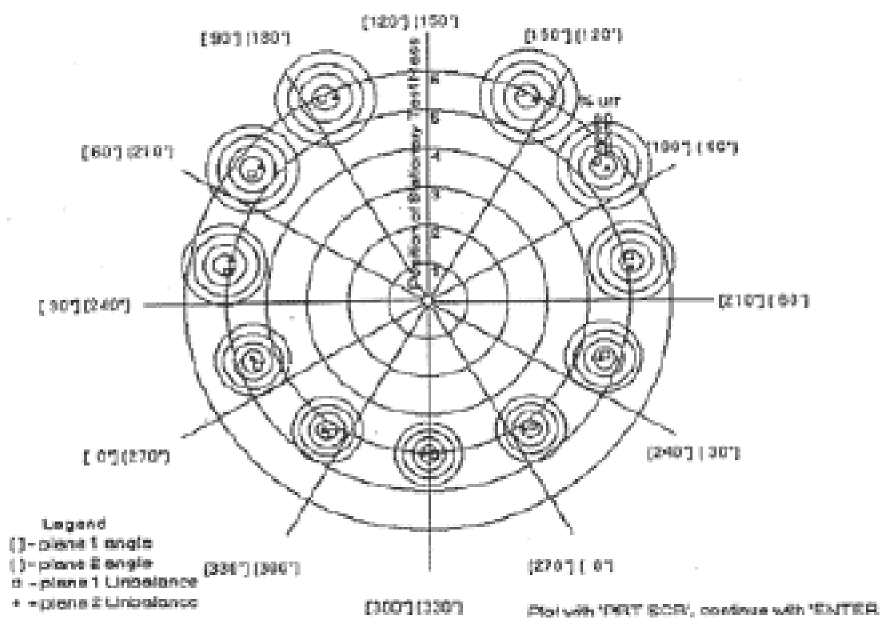
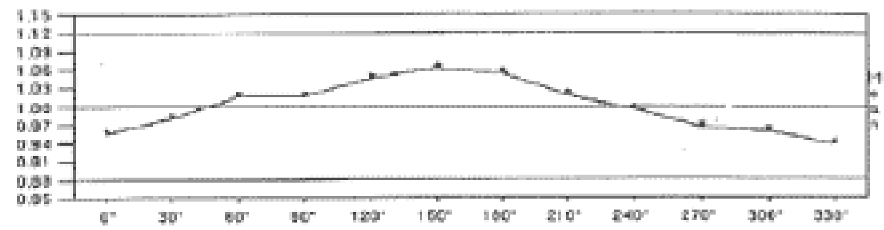
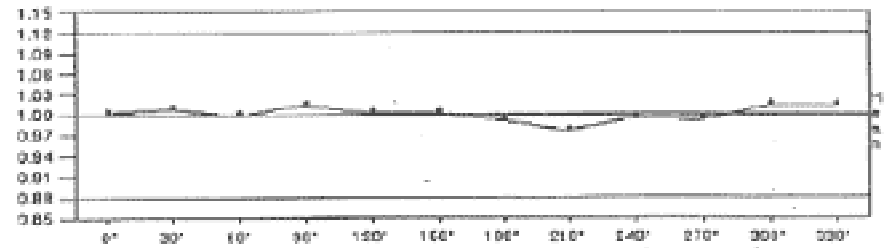


Figure 1.
Results from typical performance test with properly functioning balancing machine polar graph generated by PERFORM software published by Schenck Trebel.

End drive test for clockwise direction of rotation
Position of Test Mass Plane 1



Position of Test Mass Plane 2



Plot with 'PRT SCR', continue with 'ENTER'

Figure 2.

Results from typical performance test with properly functioning balancing machine graph generated by PERFORM software published by Schenck Trebel.

Tooling Audit and Control

Tooling is a critical element of the balancing task. Tooling design criteria are addressed in SAE ARP 1382. Tooling design is a complicated task which should not be undertaken by those who are less than completely familiar with the application and the balancing machine. However, some general guidelines are offered here for those overhaul and maintenance facilities which choose to attempt tooling design and fabrication.

Dynamic stiffness of the tooling must be sufficient to withstand the centrifugal forces that occur during balancing. However, the tooling must be of light weight to minimize the effects of additional mass upon the balancing machine. Heavy tooling in conjunction with heavy rotor weight may overwhelm the weight capacity of the balancing machine.

Mounting interfaces between tooling and rotor will possess an assembly tolerance, which may result in a runout. If this tolerance and the resulting runout are not taken into consideration, reported unbalance will reflect this source of error. If the assembly runout multiplied by the total mass of the rotor and tooling exceed the balancing tolerance, the minimum residual unbalance will be unattainable. In fact, errors due to tooling influence should not exceed 10 percent of the balancing tolerance.

Tooling should be audited and inspected periodically for compliance to specifications. Balancing tooling which falls outside design tolerances due to wear or damage will affect achievable residual unbalance. As such, it is in the best interests of the organization and the end user to conduct regular tooling audits which should include the tracking of inspection intervals, repairs, and bearing replacements. The assembly technician or balancing machine operator should conduct visual inspection prior to use, and runout checks prior to employing the tooling in a balancing process. Repeatable runout can be compensated for, non-repeatable runout or play cannot. Tooling associated with problematic balancing tasks should become the subject of a design and process review to re-examine each tool's suitability to the application.

Rotor Quality Monitoring

Process monitoring and control can be effectively applied to rotor stages and modules. Statistical Process Control is used to track a product type through its production cycle. Of course, the end product of an overhaul and maintenance facility could be a balanced rotor ready for fleet service. In this case, identical rotor stages of a single engine design can be compared using standard deviation calculations. By establishing upper and lower control limits, a non-conforming rotor can be identified and be given additional attention by engineering personnel. One example would be to monitor the number of balancing runs required to meet the balance tolerance. Figure 3 graphically demonstrates this example. Another example perhaps could be applied to rotors where blade scatter is suspected. Conducting a number of balancing runs allows the process engineer and operator to calculate the mean unbalance, which is indicative of the true residual unbalance.

Number of Balancing Runs
Needed to Achieve Tolerance

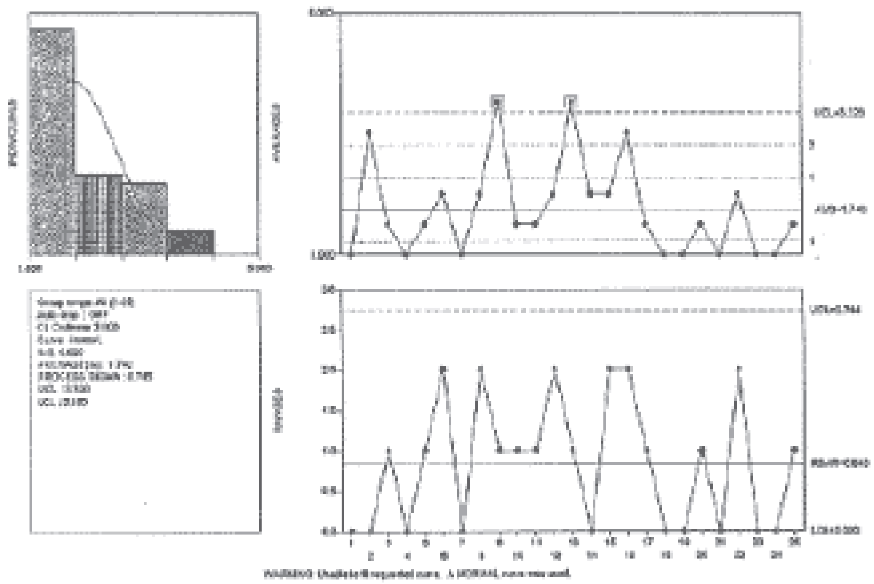


Figure 3.
Process Analysis: Number of balancing runs needed to achieve tolerance. Graph generated using Schenck's CABLINK and SPC IV software.

Process Monitoring can also be applied to track the behavior of a particular rotor stage or rotor module through its service life. By tracking each rotor by serial number and monitoring the final residual unbalance of that rotor, one can identify deviation beyond what was characteristic for that rotor previous to its most recent overhaul. As a result, isolation and troubleshooting of potential rotor problems can become more successful.

Compliance with Certifying and Regulatory Agencies

A quality control system for jet engine balancing such as the one described will contribute to safety in operation and cost containment efforts. An additional benefit will become evident when the overhaul and maintenance organization employing these techniques has elected to apply for ISO 9001 certification and registration.The SAE has published SAE Document AS9000 for organizations doing business in the aerospace industry which are seeking ISO 9001 certification and registration.

Reference List

International Standard ISO 1940/1; Mechanical Vibration - Balance Quality Requirements of Rigid Rotors - Part 1: Determination of Permissible Residual Unbalance. International Organization for Standardization Reference No. ISO 1940/1-1986 (E)

Aerospace Recommended Practice (ARP) 4048, Balancing Machines - Description and Evaluation Horizontal, Two-Plane, Hard Bearing Type for Gas Turbine Rotors. Society of Automotive Engineers, Inc. 1993-08-17.

ARP 4050, Balancing Machines - Description and Evaluation Vertical, Two-Plane, Hard Bearing Type for Gas Turbine Rotors. Society of Automotive Engineers, Inc. 1994-07.

ARP 4162, Balancing Machine Proving Rotors. Society of Automotive Engineers, Inc. 1993-09-28.

ARP 1382, Design Criteria for Balancing Machine Tooling. Society of Automotive Engineers, Inc. 1977.

Aerospace Standard AS9000, Aerospace Basic Quality System Standard. Society of Automotive Engineers, Inc. 1997-05.

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