Engine Performance Improvements and shop Efficiencies through the Geometric Balance Engine Core Assembly Process ("GeoBal")

Introduction

Axiam's GeoBal Engine Core Assembly Process can improve engine performance and engine shop efficiencies when installed in your MRO engine shop. Axiam's proprietary computer technology enables an engine shop to build engine cores optimally (closer to its design than any current methodology) for each set of parts. Optimized blade tip clearances bring improved SFC, EGT Margins and Vibration levels as measured in the test cell. Straight engine core builds about the actual centerline of rotation also enable these performance improvements to remain stable on wing and prevent many of the common engine problems seen in the engine shop and on wing. Axiam's repeatable assembly processes build straight engine cores (rotors, mating rotors to shafts, bearing compartments, seals, casings & blade distribution) about the actual centerline of rotation for each rotor stage and engine core module thereby optimizing blade tip clearances and balancing each stage during assembly. To date, Axiam has delivered assembly processes for 54 engine models and 51 customers.

Cooperation among the airline, engine shop and Axiam would bring significant fuel cost savings to the airline and cost savings to the engine shop. Axiam's repeatable engine core assembly processes typically deliver the following engine average performance improvements compared to the engine manual and other known assembly processes that include software: 2-6% SFC; 40+% EGT Margin; EGT Margin Stability on Wing; and, 30+% Vibration reduction. Additionally, the engine shop would experience substantial assembly time reduction, avoidance of typical assembly/balance problems, improved throughput, as well as, significant cost savings. Additional revenues accrue for any PBH contracts as Axiam-built engines stay on wing longer.

In over 30 years in business, Axiam has found that engine performance issues always seem to have several underlying drivers. The engine shops often address the symptoms without fixing the underlying problem cause. Our engineers use a data-based analysis methodology of the engine shop workstation activities and material flow that impact the assembly/balance workstations to develop workstation baselines of appropriate performance in support of repeatable engine core assembly/balance; and, then develop repeatable, optimal engine core assembly processes in our laboratory. The lead time is 4-6 months for installation and training of the complete engine core assembly process. After process installation and training of shop personnel, Axiam would perform ongoing preventive maintenance including refresher training, preventative and emergency service. Axiam engineers would be available 24/7 to provide ongoing engineering support to help solve any engine core build issues encountered in the shop.

Engine cores (rotors, mating rotors to shafts, bearings, seals, casings & blade distribution) are built straight about the calculated actual centerline of rotation. The interactive and predictive software build models mathematically optimize blade tip clearances and disc balance at each rotor stage during assembly by building the engine core from the actual centerline outwards to the casing. Optimal builds are always accomplished on the first pass (no rebuilds, no blade swapping). This opportunity is unique because neither the engine OEMs nor other suppliers can provide such repeatable, optimal engine core assembly processes despite their representations to the contrary.

Current Engine Manual Build Practice

A bladed rotor includes a central hub, one or more discs and multiple blades secured to their respective discs and projecting outward from the hub. The bladed rotor rotates about a longitudinal central axis. However, because of the non-uniform distribution of mass within the rotor assembly and the blades, it is difficult to achieve a perfect balance for a bladed rotor. The minimization of imbalances is essential for minimizing vibration and noise and maximizing the efficiency and performance of the rotor and turbine engine.

The typical engine manual practice is to balance rotor assemblies by separately balancing each disc and aligning individual rotor discs in the assembly so that the high point of one disc is offset by the low point of its adjacent disc. The blades are distributed by mass about the theoretical geometric centerline of each disc. The main drawback of this methodology is that it is a "trial-and-error" method which does not guarantee the optimal alignment of the rotor assembly because the separate actual centerline of each disc is not aligned with the actual centerline of the rotor assembly. The blades may then be redistributed about each disc in an arbitrary, trial-and-error manner in the hope of achieving some acceptable balance. A static balance machine may also be used to add weights to the disc or blades to help in achieving a rudimentary balance. Consistency and repeatability is missing in this trial-and-error procedure. Often excessive time is spent achieving an acceptable balance.

GeoBal Engine Core Assembly Process Description

GeoBal addresses the shortcomings of the engine manual methodology and provides a computer method and system for optimally balancing engine rotors during assembly on the first pass. GeoBal calculates the best-fit stack of the discs and the optimal blade distribution about the centerline of rotation of the rotor assembly. It defines an actual centerline of a geometrical/ mathematical model of a rotor assembly as a whole. Based on the defined centerline, the system calculates a centerline deviation of each disc of the rotor assembly. After calculating the best fit centerline deviation for each component, GeoBal determines an angular location of the component. GeoBal next determines the centerline deviation and angle of each disc based on the centerline of both ends of the subject module as stacked and determines disc blade distribution based on the calculated centerline deviation and the angular location of the disc/component. Determining rotor blade distribution includes weighing each rotor blade for the disc/component by either pan weight or moment weight, as appropriate.

Each rotor blade for a given disc is identified by a serial number, bar code label and a blade weight. The blade distribution is computed in order to offset the centerline deviation of the disc. The process of offsetting the discs' centerline deviation optimally balances the rotor assembly/module. This rotor blade distribution per disc is displayed to a user in both a numerical and graphical format. After determining the rotor blade distribution, the rotor blades are assembled on each disc using the displayed information. The resulting rotor assembly is then verified against the computer model prediction. It should be understood that this method can be applied to a combination of rotors (compressors and turbines) with their respective shafts or hubs.

Some of the tasks required to implement the GeoBal assembly/balance process are already part of the engine shop's current procedures. Other tasks will replace a current procedure, such as weighing and marking the blades with the Axiam scale/printer system for use in

GeoBal/SuperStack software calculations, and SuperStack predictive build plans in lieu of taking intermediate runout measurements during the rotor assembly. The Axiam GeoBal/SuperStack blade distribution model will replace the current method of blade distribution for all rotor stages. Discs/spools that are normally bladed individually with an OEM method will use the GeoBal/SuperStack calculated blade distribution instead. Physical blading of discs/spools will therefore take an equivalent amount of time using this new method. Certain procedures, like our blade distribution calculations, will save time by reducing and/or eliminating lengthy blade swapping methods during the rotor balancing procedure. Furthermore, utilizing stack plans calculated with GeoBal/ SuperStack, all rotors will be built optimally on the first pass and will not require rebuilds, which are extremely time-consuming (average 3 rebuilds per rotor in CFM56 tests). This is possible because Axiam's assembly processes are repeatable while the Engine Manual processes are not repeatable.

Axiam's GeoBal/SuperStack software aligns in its predictive build models the engine's dynamic structure (rotors, shafts, bearings/seals & blades) with its static structure (bearing housing & casing), thus improving overall engine performance and wear. Because the rotors are built optimally for each set of given parts, tip grind will have minimal effect on GeoBal/SuperStack calculations which will distribute blades with respect to the actual centerline of rotation of the engine core, also taking into account material properties of part unbalance. The rotors are mated optimally to the shaft through the GeoBal/ShaftMate software which further saves time. The GeoBal/BearingStack and GeoBal/SmartCase software modules ensure the bearings/seals and casings builds are optimal for each particular set of parts and share a common centerline of rotation or concentricity to the rotors and shafts.

GeoBal Procedures Outline

Rotor Builds

Measurement of piece parts on Axiam gage system.
Weigh and print barcodes on blades in blade kitting area.
SuperStack software calculates rotor build models and blade distribution.
Build rotor (first pass) in hydraulic tooling and distribute blades according to SuperStack model.
Verification of optimal build via Axiam gage measurement.

Rotor Mating

ShaftMate software calculates optimal (straight & to centerline) rotor mating to shaft for each specific rotor.
Perform rotor mating utilizing ShaftMate model.

Casing

Measurement of casing piece parts on Axiam gage system.
Casing is measured and SmartCase software ensures each casing's predictive build model concentricity is compatible with the engine core actual centerline.

Unique GeoBal Features

Production efficiencies are achieved by always producing optimal, straight engine core builds on the first pass, shortening assembly times, eliminating rebuilds, eliminating test cell rejects due to vibration and avoidance of many typical engine issues. The straight, optimal builds coupled with fully seated parts and alignment of the dynamic/static structures contribute to improved engine performance as measured in the test cell and on wing. Axiam's unique features include:

Straight Build models are developed in the software; they start with highly-accurate parts measurement data. As each part in an assembly is measured (rotors, shaft, blades, casing, & bearings), a predictive stacking model identifies the straightest possible stack about the actual centerline of rotation at each stage for that combination of parts. The complex mathematics in the software was developed in partnership with the Massachusetts Institute of Technology math department.

Optimal Builds are generated in the integrated, predictive software build models, after parts are measured, by orienting the parts as straight as technically possible about the centerline of rotation and mathematically correcting for any part distortion. A part change would result in the generation of a new optimal build model.

Fully-Seated Rotor Assemblies are achieved through the application of pressure evenly to the rotor assembly within Axiam's proprietary hydraulic assembly tooling. Once fully seated, the bolting of the rotor is used to secure the seating while the rotor assembly remains under pressure. Assemblies built using Axiam's methodology do not experience "rotor shift" in the test cell, preventing "rotor bow" that brings test cell rejects due to vibration and relatively poor engine efficiency.

Proprietary Assembly Procedures are developed to achieve assembly process repeatability and optimal, straight builds. Typically, about 10 percent of the assembly procedures in the engine manual are modified to achieve repeatability.

First Pass Success means that the actual build approximates the predictive stacking model target build on the first attempt. The time to measure parts, assemble the parts in Axiam's build tooling, and to compare the actual build to the projected optimal, straight-build stacking model is always consistent for each build. First pass success translates into a two-thirds reduction in total assembly/balance time.

Structural Alignment is achieved in the applications software build models. The integrated predictive build models ensure structural alignment. It is essential that the raw measurement data be as accurate and error-free as possible to optimize the alignment.

Disc Balance during Assembly is calculated in the SuperStack/BladeDistribution software and displayed in a predictive build model. The unbalance of each disc is offset by the blades placement so as to minimize the need for trimming.

Total Assembly/Balance Time Savings

Total engine core assembly times are dramatically reduced and are predictable despite the need to measure all parts. Part set-up and measurement takes 4-5 minutes per part and 30-40 seconds per blade. Blade measurement data is electronically transferred to the gage computer software for integration into the predictive build models with other engine core parts data. The following is a list of assembly/balance time savings features when using GeoBal:

- Reduced time to measure and build each module.
- Integration of all engine core modules.
- Optimal builds on first pass; elimination of rotor rebuilds.
- Elimination of test cell rejects due to vibration.
- Optimal blade distributions on the first pass (no reallocating blades for balance prior to grinding). Blade mass data is integrated with other parts' data to mathematically offset unbalance of each disc.
- Optimal mating of rotors to shaft or other rotors on first pass.
- Reduced balance and trim times because rotors already balanced mathematically.
- Blade marking performed by printer; blade data transmitted electronically.

- All measurement data managed electronically.
- Assembly times consistent for each engine model.

Competitor's Assembly Processes

There exist other "copy-cat" assembly processes which claim to build straight rotors, engine cores, and optimize results, but they make false claims. Axiam's testing has shown that the "copy-cat" product results are worse than simply using the traditional engine manual procedures, tooling and hand-held measurement devices. Their products consist of a "trial-and-error" methodology in which an electronic rotary table with measurement arms of relatively low 2-D measurement accuracy (+/- 0.0005") and rudimentary rotor stacking software (projects each disk to a bearing journal) are used with the engine manual assembly procedures and tooling. Their offering consistently creates bowed builds that result in sub-par engine performance and added engine shop costs. This is in contrast with Axiam's relatively high 3-D measurement accuracy (+/- 0.000020") and a family of integrated software modules, assembly procedures and tooling for the entire engine core. Only Axiam holds the patents for straight engine core builds about the actual centerline of rotation of each rotor stage and engine core module.

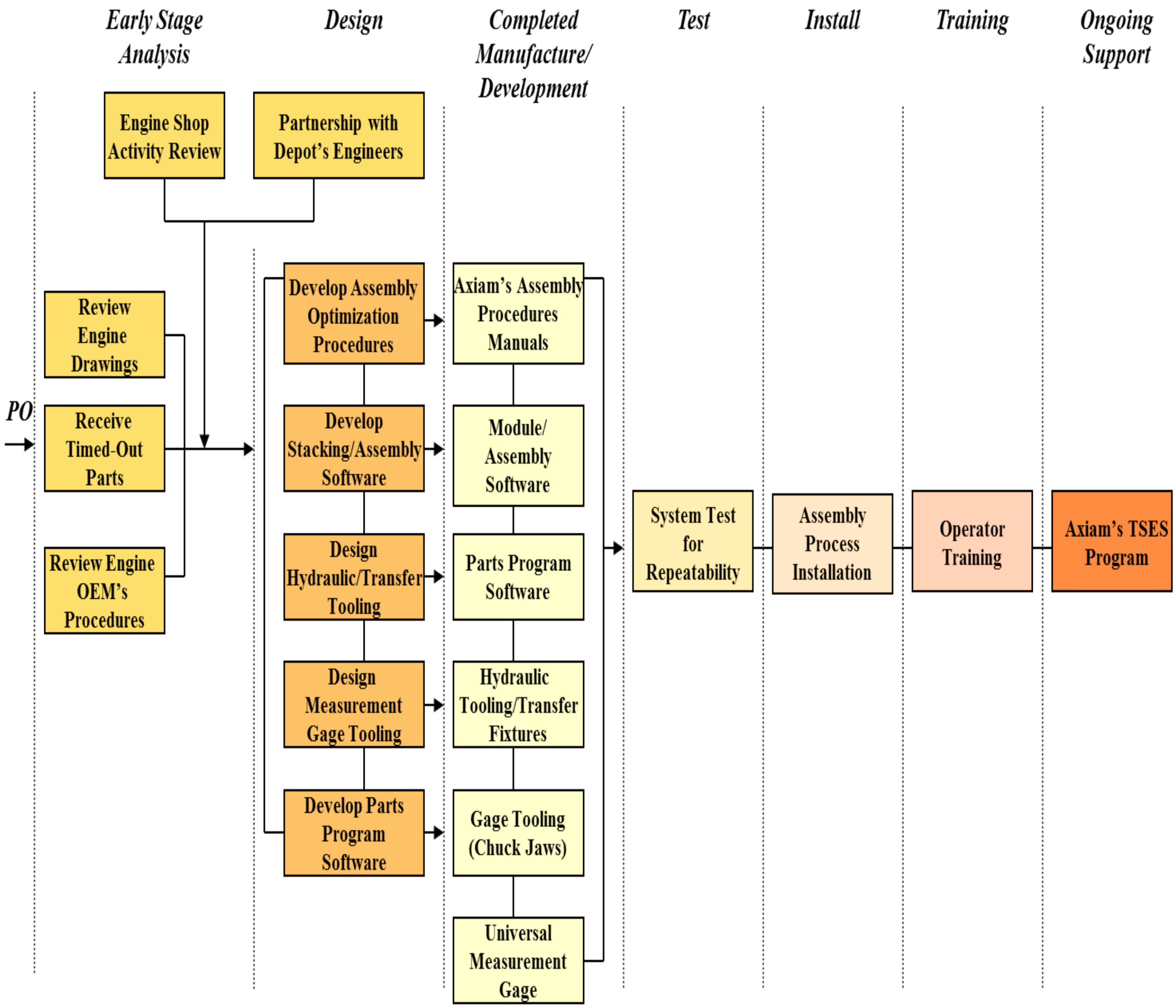
Patent Protection

Axiam possesses the rights to computer-based engine core assembly of rotors, blades, shafts, seals, bearings and casings. Axiam holds several patents for the computer-based assembly of turbine engine cores: 1) Rotor Assembly System and Method, U.S. Patent 6,898,547; 2) Method and Apparatus for Geometric Rotor Stacking and Balance, U.S. Patent 7,539,594; 3) System for Optimal Alignment of a Bearing Seal on a Shaft of a Gas Turbine, U.S. Patent 7,565,257; 4) System for Optimal Alignment of a Shaft of a Gas Turbine; and 5) Calibration and Use of an Absolute Diameter Measurement Arm.

GeoBal Development Activities Flowchart

Axiam creates a custom developed solution for each engine core model. All components of its engine core solution are designed to achieve specific objectives. The key development activities for a project are highlighted below:

Engineering Analysis/Development Activities



Summary

Axiam expects to bring significant improvement in engine performance and engine shop efficiencies that would generate substantial cost savings annually for the engine shop and operator. The typical financial payback from total cost savings is within a year.