Precision Engineering 38 (2014) 379–390

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

An assessment of "variation conscious" precision fixturing methodologies for the control of circularity within large multi-segment annular assemblies☆

Stewart Lowth, Dragos A. Axinte*

Rolls-Royce UTC in Manufacturing Technology, University of Nottingham, UK

ARTICLE INFO

Article history:
Received 4 February 2013
Received in revised form
20 September 2013
Accepted 4 December 2013
Available online 25 December 2013

Keywords:
Fixturing
Assembly
Circularity
Segmented annular assembly
Variation conscious
Build methodologies

ABSTRACT

The fixturing of large segmented-ring assemblies is of importance to a number of key high value industries such as the aerospace and power generation sectors. This study examines methods of optimising the circularity of segmented-ring assemblies, and how the manufacturing variation within each element (i.e. segment wedge) contributes to overall assembly variability. This has lead to the definition of two original assembly methodologies that aim to optimise an assembly, so that circularity errors are minimised for a given set of components. The assembly methods considered during this study include a radial Translation Build (TB) and a Circumscribed Geometric (CG) approach, both of which are compared to a traditional Fixed Datum (FD) build method. The effects of angular, radial, parallelism/flatness and chord length variability within the component geometry, and their effect on the circularity of the final annular assembly are examined mathematically and experimentally. Furthermore, the inherent loss of assembly circularity due to differences between component and assembly sagitta is also considered, along with the stepping caused by dissimilar adjacent component radii as a result of manufacturing variation. Experimental results show that the CG build method offers a significant improvement in circularity in most situations over the benchmark FD build method. This contrasts the TB results that proved to be the least consistent in terms of circularity, but better in the control of angular breaking errors within the assembly.

1. Introduction

The creation of large geometrically accurate annular components is of importance to a number of manufacturing industries such as aerospace and power generation. These high precision rings are frequently manufactured using a stock material or a near-net-shape blank, on to which various conventional or non-conventional machining processes are employed until the final geometry is achieved. However, as the ring size or geometric complexity increases, it may become economically or technically beneficial to assemble the ring from smaller segment components. The down-side to this is that the additional assembly stages will inevitably introduce new sources of possible variation into the production process.

It is common practice, where the production of repeatable components is required, that jigs and fixtures are used to aid the process of manufacture. These manufacturing aides deterministically locate and securely clamp single or multiple workpieces, permitting one or more stages of manufacture to be performed. They offer a beneficial impact on the manufacturing process in terms of productivity, cost-per-part and quality [1]. However, designing and manufacturing a fixturing system for a specific task can be both time consuming and expensive, with their creation constituting 10–20% of the total set-up cost of a manufacturing process [2]. Moreover, a badly realised fixture concept can lead to manufacturing and machining errors through poor location, flexing of the fixture or geometric inaccuracy [3].

It is scientifically well established that a 3-2-1 location datum methodology offers reliable deterministic positioning of a workpiece relative to its fixture. Nevertheless, even using this conventional approach positional variability will occur [4]. This is especially the case when fixturing an assembly (e.g. Fig. 1), as the location of components is defined by the other components within the assembly as well as directly by the fixture. Camelio et al. [5] expressed these location errors as the deviation between the world coordinate system (WCS) or workpiece nominal position and

* Corresponding author. Tel.: +44 (0) 115 951 4117.
E-mail address: dragos.axinte@nottingham.ac.uk (D.A. Axinte).

http://dx.doi.org/10.1016/j.precisioneng.2013.12.004

Nomenclature

EIC_i	effective inner chord length for component i, adjusted for out-of-plane error (mm)
I_a	identifies inner face a
I_b	identifies inner face b
IC_i	inner chords of component i, generated via IR_i a and $I\theta_i$ (mm)
IC'_i	adjusted inner chord for component i, based on IR_i and γ_i (mm)
IR_i	inner radius of component i (mm)
$I\theta_i$	inner angle of component i, between faces I_a and I_b
n	number of components in annular assembly
O_a	identifies outer face a
O_b	identifies outer face b
OC_i	outer chord of component i, generated via OR_i and $O\theta_i$ (mm)
OR_i	outer radius of component i (mm)
$O\theta_i$	outer angle of component i, between faces 0_a and 0_b
P_a	out-of-plain measurement (parallelism) of component, between face I_a and O_a (mm)
P_b	out-of-plain measurement (parallelism) of component, between face I_b and O_b (mm)
RA_i	radial assembly position of component i, for the translational build assembly method (mm)
R_b	nominal assembly inner radius diameter (mm)
R_{cir}	theoretical build radius of circumscribed geometric (GC) assembly method (mm)
SA_i	sagitta for chord EIC_i and theoretical assembly build radius R_{cir} (mm)
SC_i	sagitta for chord EIC_i and inner radius IRC_i of component i (mm)
α_i	angular position of fixture datum locator i, for circumscribed geometric (CG) build method
β_i	angle of component inner chord relative to assembly centre
γ_i	calculated true angle of across component
ε_i	inherent loss of circularity due to sagitta differences between assembly and component (mm)
$\varepsilon_{\max}$	the largest value of ε_i within the assembly's components (mm)
ρ_i	deviation (stepping) of component i from assembly build radius (mm)
φ_i	breaking angle between assembled components

Local Coordinate System (LCS) or workpiece measured position; a homogeneous transformation matrix, within Euclidean space using Cartesian coordinates express this deviation. This matrix describes the Six Degrees of Freedom (6-DOF), by combining the three orthogonal *XYZ* translations and the angular rotation about the *X*, *Y* and *Z* axes, as required for the positioning of the workpiece within three dimensional Euclidean space. Song and Rong [6] built on the homogeneous matrix method and the 3-2-1 methodology, to propose a technique for establishing if a component is over or under constrained by its fixture. More recent scientific interest has been focused upon variation propagation within multi-stage manufacturing processes using a mathematical state-space model [7–10], commonly referred to as the Stream-of-Variation (SoV). The SoV paradigm combines the error contributions in matrix form from the current and preceding manufacturing operations, manifesting the result as a state vector representation of the total error in the current process.

Predicting the quality of workpiece-fixture location compliance is also an important consideration in the understanding of fixturing error, on which topic a number of scientific reports have been published [11–13] using a Finite Element Analysis (FEA) approach. These studies examine the clamping of components misshapen by manufacturing errors, with respect to component deflection and fixture deformation as a result of the changes in fixture reaction forces. The idea allowed for the adjustment of successive CNC machining operations to compensate for the errors, Abellan-Nebot et al. [14] proposed fixture embedded sensors to measure workpiece error. Furthermore, a number of active fixture design approaches have also been proposed [4,15–17], where location and clamping conditions are adjusted to balance errors transmitted from previous manufacturing stages. The fixture compliance and the active clamping studies published to date have generally concentrated on how a single component interacts with its fixture, but there has been little consideration of multi-part assemblies. When considering an assembly it is usual that some of the degrees of freedom for the individual components are constrained by their interface with other assembly components, rather than the fixture itself. These component–component interactions will play a role in deformation modes and conformity when considering the clamping forces in a fixture.

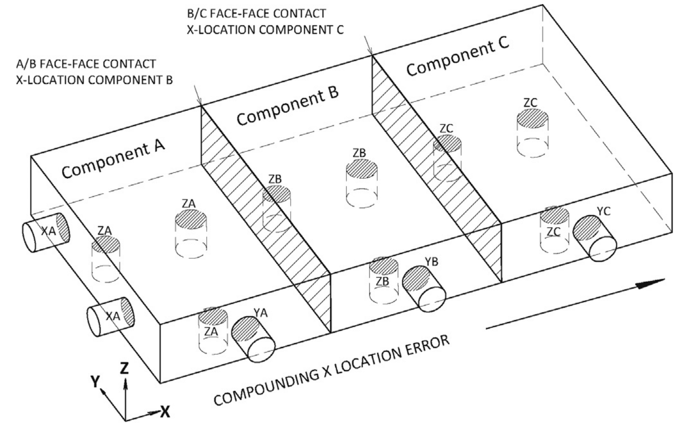

Fig. 1. Face–face location of assembly components.

In the main, the interest of the science within the field of fixturing has been levelled at deterministically holding a single component. However, Huang et al. [18] extended the SoV methodology to propose a model for the assembly of rigid-bodies within a single fixture. Various types of inter-component joint types were mathematically defined with two matrices. The first, called the "twist matrix" which defined the DOF in which the component was kinematically permitted to move, while the second "wrench matrix" contained the remaining constrained DOF. Validation of this SOV method was carried out using a 10,000 item Monte Carlo study, which was compared to a 3DCS Analyst a commercial Computer Aided Tolerancing (CAT) system, using a 5000 item study. The Monte Carlo SOV and CAT results were found to be <1.5% different in their results.

Two related studies [19,20] attempting to minimise axial error build-up within the linear stacking of cylindrical gas turbine components have been conducted. The authors used various build protocols in an attempt to evaluate and improve the co-axiality between segments and thus build a straighter final assembly. Both studies showed the optimum build algorithm to be one of minimising the distance between the component axis and the axis of the reference "table", rather than minimising the component–component axial distance. Although the face–face stacking contact is analogous to the inter-component contact seen within a segmented-ring assembly, these studies are based very specifically on linear assemblies where the use of cylindrical segments allows for the rotation of a component to improve its fit. This advantageous situation cannot