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System for Recirculation of Mobile Tooling

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ABSTRACT

Aircraft assembly systems which require tooling or machinery to pulse or move between multiple positions within a factory can be positioned with high repeatability without high performance foundations or sweeping out large areas of floorspace. An example shows a system of large left and right-hand frames which are positioned at 3 sequential manufacturing steps and then recirculated to the start of production via a central return aisle. The frames are 41 ton actual weight and are 72′ long, similar to a rail car. The system achieves rectangular motion for the recirculation path. The supporting and moving system incorporates low-cost rail in a floor with minimal preparation and simple to use controls. The system is also easily reconfigured if the manufacturing system needs to be altered to meet rate or flow requirements.

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INTRODUCTION

Airplane wing components require precise placement relative to one another prior to fastening. Overall positioning affects the shape of the wing, while local components such as flaps have shafts running through multiple sets of concentric bearings requiring more precise local positioning. Fixtures for smaller parts can be mounted on only a few points so the foundation will not affect the shape of the fixture, but longer parts are usually connected to the foundation at many locations and require a stiff foundation to maintain accuracy. Tooling fixtures that can be moved around a factory have usually been allowed to deform more while being moved and are then located with precision embedments in the floor to bring them back to a precise configuration. If the tool is used in multiple locations in the factory or if there are multiple tools using the same embedments, very tight tolerances must be maintained in both the embedments and the tools as any deviation in either will cause a deviation of similar magnitude in the wing component positioning due to the tight coupling between the embedment and the tool.

A system which insulates the fixture from deviations in the floor embedments can decouple the tolerance requirements of both the fixture and the floor. A suspension system using railroad springs, precision linear guides, and pneumatically actuated rail brakes provides this decoupling. The springs provide a supporting force rather than a supporting datum. The floor stiffness requirements are significantly reduced. Once the requirement for precision floor embedments is removed, the opportunity to use relatively low-precision in-floor rails with robust, low-friction wheels enables a floor-based motion system. This eliminates the need for factory cranes for pulsed motion between assembly stations. The low friction of the rail system enables motion using relatively low-cost manually-driven electric tugs to move even large fixtures between stations. The guiding rails prevents free motion of the fixtures making the operator's job easier by constraining the fixture to a path. Alternative motion systems including drag chains could be used but these are less flexible and require significant detail in the floor.

In an organized factory, direction changes of the fixtures on the line occur at defined locations. While direction-changing hardware such as turntables can be integrated into the floor, experience has shown the installation and maintenance of motors, drives, bearings, switchgear, and related components under the floor is difficult. In the system presented, lateral motion and recirculation of the fixtures is enabled by a second set of wheels and rails in the perpendicular direction. A simple drive system engages and disengages the second set of wheels while supporting the fixture using the suspension system. This eliminates a change in boundary conditions for the fixture with change of direction. Additional direction change points can be implemented by simply laying more rail rather than layout changes involving additional turntables.

A key difference between this method of moving fixtures within the factory and a conventional system with precision embedments involves the leveling of the fixture. In the conventional system, the level is set by the embedments and can be precise and repeatable. The tolerance requirements are typically driven by the ability of automated systems to datum and orient the part program relative to the fixture. In the system presented, the relationship between the shape and location of the fixture and the level of the rails in the floor is driven by the spring rate of the suspension system. While this can be highly repeatable, changes in the weight distribution of the fixture, for example when aircraft components are added and removed, cause the nominal level of the fixture to change. While this has minimal impact on manual work or locally applied drill plates, automated systems not attached to the fixture need to accommodate the level variation. The robotic drilling machine that interfaces with this fixture will measure three datum points on the wing surface and calculate the location of the wing relative to the machine. Holes can then be drilled accurately relative to the wing surface regardless of the location and orientation of the wing.

DEVELOPMENT OF THE CONCEPT

Alternatives Considered

One alternative for moving large frames around a factory is shown in Figure 1. This system rides on casters which include jacks to lift the fixture and lower it onto precision locating devices. This system works well for smaller tools but it becomes difficult to achieve and maintain the required accuracy on a larger tool that needs more than four points to support and locate the system. Caster loads on the floor can also be excessive.

Figure 1. Alternative caster-supported system considered

A standard bogie rail system was also evaluated but requires an excessive length of factory space to transition to a parallel track, would require custom features to lock the position while in station, and require the fixture base to be higher than desired.

System Overview

An overall view of the system is shown in Figure 2. The main components are the fixture itself, the tooling inside the fixture, the wheeled suspension system, the tug, and the in-floor rail system.

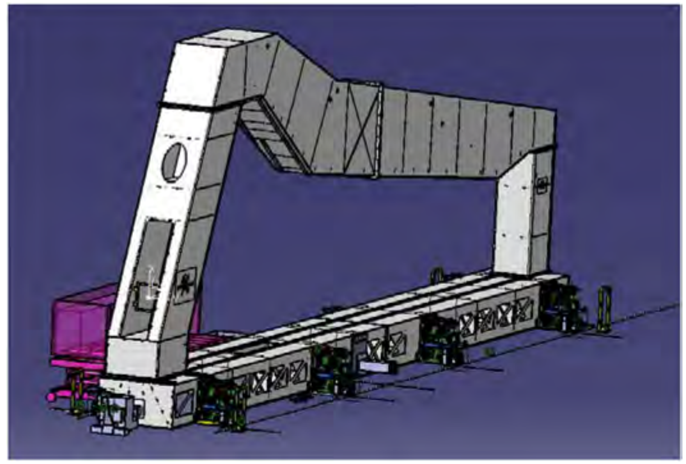


Figure 2. System overview

Pulsed Line Process

The fixture is supported by the wheels on the rails at the first position in the build process. The rail brakes are engaged by connecting compressed air to the fixture. A shot pin to the floor locates the fixture in the longitudinal direction. Aircraft components are loaded into the fixture. The shot pin is retracted and the brakes released. The fixture is then pulsed to the automated drilling position via an electric tug which attaches to a bracket on the end of the fixture. At the drilling position the shot pin engages a new longitudinal location and the rail brakes are engaged. Automated drilling and some manual work is undertaken. The shot pin is retracted and the brakes released. At the final position the pin and brakes are engaged, manual work is completed, and the wingbox is unloaded. Following unload, the brakes are disengaged, the lateral wheels are actuated downward to lift the fixture off the primary rails, the tug is brought around to the side, air and electric are disconnected, and the fixture is towed sideway to the recirculation lane. The wheels are then engaged on the recirculation rails and the fixture is towed back to the start of the line.

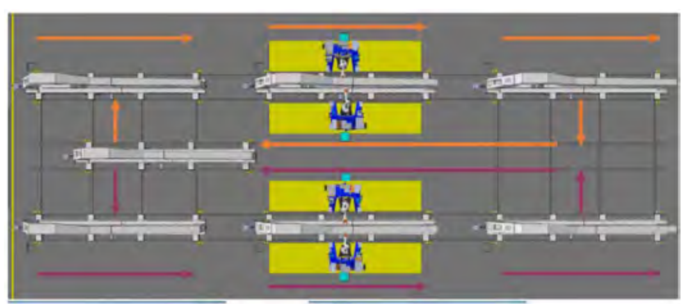


Figure 3. Recirculation pattern

Design Approach

The overall approach to the design begins with sketching a fixture to fit around the tooling holding the aircraft components. This fixture is optimized for weight considering the deflection under live load versus the section properties of the fixture, the number and location of supporting wheel systems, and the spring rate of the suspension system.

A tooling concept is sketched around the customer-provided aircraft geometry which in this case is for an aluminum aircraft wingbox. This tooling is conventional in that it picks up control surface hinges and other index features. The tooling is attached to aluminum base plates which are parallel to the spar web planes. These subassemblies are built off-line. The fixture beams are made of steel and thermal differentials along the length of the wingbox are accommodated by linear guides between the base plates and the fixture. Thermal growth in the vertical direction is accommodated by aluminum towers supporting the upper beam.

The interface plane where the linear rails attach to the fixture is declared as a technical interface between the tooling and the fixture.

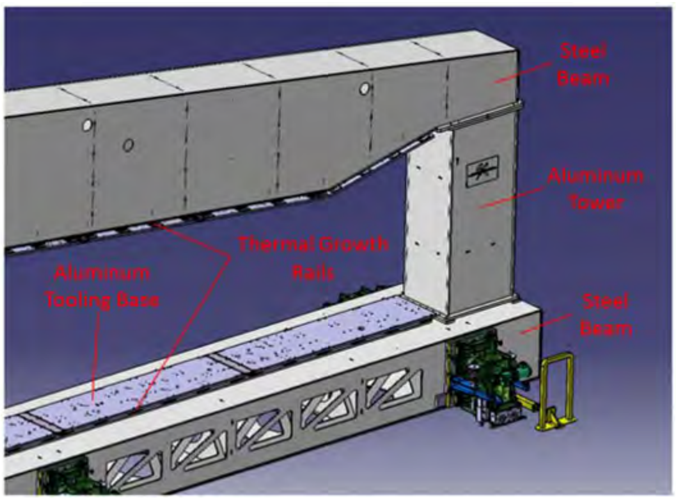


Figure 4. Thermal growth rails and fixture materials

Overview of Analysis

The overall goal of the analysis is to limit the deflection of the tooling points under live load and as supported by the fixture and the suspension system below the build tolerance with a factor of safety.

Once the interface planes are defined, a fixture structure can be sketched around those planes. The tooling design can mature somewhat independently of the fixture from this point. Other considerations include the desired working height of the workpiece above the factory floor, part loading, access for automation, access for manual work, and access for decking and platforms.

Hooke's Law shows how the spring rate of the suspension system drives the changes in forces supporting the fixture as a function of the level of the floor rails. A first iteration of the spring rate can be driven by the commercially-available options in railroad springs.

"Spring" boundary conditions were used to support the fixture at the 8wheel locations in the FEA model.

Using the mass and center of gravity information for the wingbox, live load distributions can be developed for application in FEA to the fixture for various loadcases. Other loadcases can include forces from automated equipment, seismic stability, loads from the tug system, and the weight of operators moving around the fixture.

Index points in the model correspond to hinge points and other features of interest for deflection simulation. The tooling flags were modeled with a relatively high Young's Modulus so as to not contribute to the deflection result. Remote Points are another way to handle this in FEA.

The analysis was undertaken by importing the geometry of the fixture into ANSYS Workbench 15.0.7. Standard linear static structural analysis was performed.

For each load case, the deflection of the index points in the FEA model as a result of the loads was extracted to Microsoft Excel. In Excel the points were analyzed for their deviation from the nominal location.

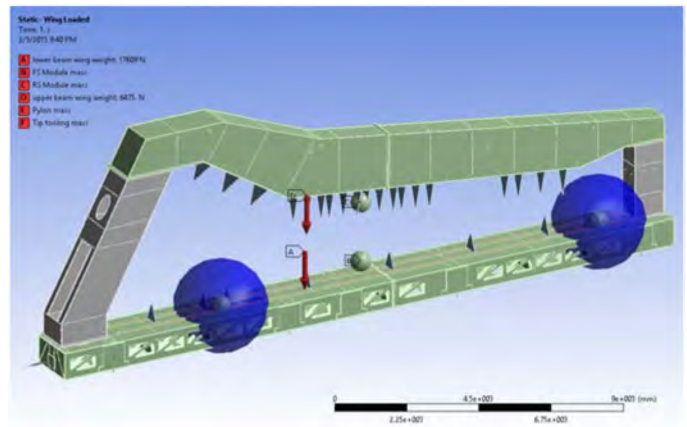


Figure 5. Typical FEA loadcase

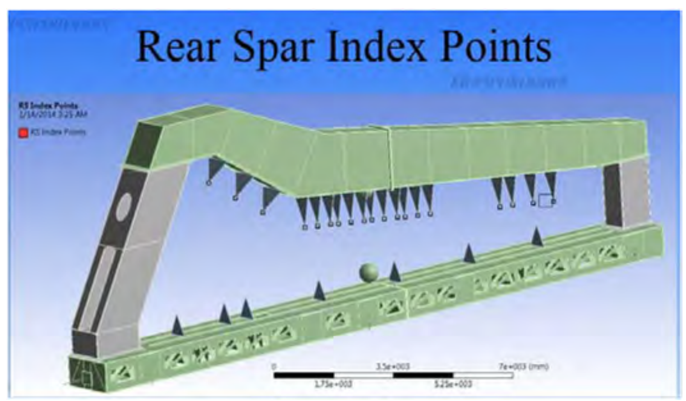


Figure 6. Example tooling index points where results were extracted

Sprung Wheels on Rails

The spring rate of the frame is the force required to deflect the frame a given amount. The sensitivity of the system is a function of the spring rate of the frame and the spring rate at each wheel assembly. By using a low spring rate at the wheel assemblies, a large deflection in the floor rail will result in only a small change in the shape of the fixture. Required build tolerances are maintained even with several millimeters of rail misalignment. This ability to maintain accurate component positioning over changes in floor shape allows less frequent realignment of the tooling due to settling of the foundation. A larger deviation is allowed while moving the fixture between stations because components are not being set at that time. When the fixture is located in a work station brakes on the vertical rails of the wheel system are actuated at each wheel assembly to lock the current position of the fixture in space. These brakes are sized to resist all live loads placed on the fixture such as robotic drilling equipment pressing on the wing skin, personnel walking on the fixture doing manual operations, and loading and unloading of parts. At the completion of work in the cell the brakes are released while the fixture is moved to the next work cell. Once the completed part has been unloaded from the last cell the fixture is ready to be recirculated back to the first cell. To move the fixture laterally a second wheel cassette is driven down by a linear actuator, lifting the longitudinal wheel cassette clear of the rail. This system of separate wheel cassettes for perpendicular motion allows simple fixed crossover points to be used in the floor rather than a more complex wheel turning system. The actuator system also provides easy maintenance of the wheel cassettes as only one cassette in the assembly is under load at a time, allowing the other to be replaced if needed.

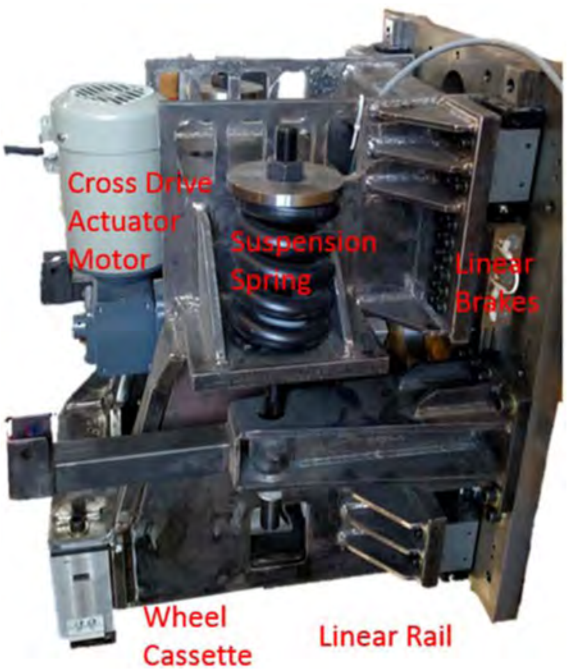


Figure 7. Wheel System Prototype Details - View from Above

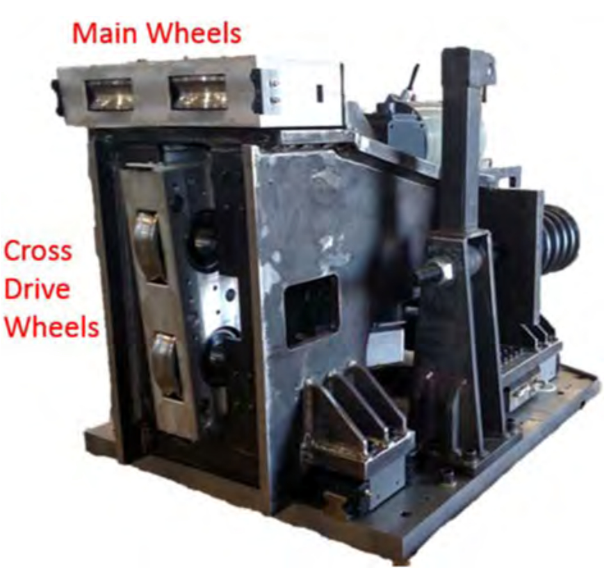


Figure 8. Wheel System Prototype Details - View from Below

Analysis Results

This particular frame was designed such that the index points should return within .15mm of nominal when the floor rails are within 1mm of level. This would be the desired level within a build station and considering a range of live loads coming in and out of the fixture. Between build stations the index points should stay within .4mm of nominal with the floor allowed to be out of level by 3mm. Typical predicted results are shown below.

Figure 9. Example of Deflection Predictions for a Live Load

PHYSICAL TESTING

Performance of the fixture and moving system compared to deflection requirements and verification of the FEA model was determined by physical testing.

Floor rail accommodating a move of approximately 30% of the length of the fixture was installed. Cross rail for use in testing the lateral moves and repeatability was also installed. The floor rail was applied directly to the surface of the existing factory floor, spanning several expansion joints. The floor in the test area is 8″ wire reinforced concrete on a subgrade modulus of approximately 200 lbf/in^3. The rail level was measured with a laser tracker and was found to be straight and level within +/−4mm over the entire length. However, significant short-period deviations on the order of 1mm/m were also present.

The linearity and rate of the springs was verified using a Tinius-Olsen type machine. A small sample size of springs were measured and found to match the catalog rate within 5%.

A Jig Reference System was created by fixing tracker nests to the aluminum base plates.

Simplified tooling was fabricated to provide load adapters for the fixture. Test weights representing the weight of the actual tooling were applied to the load adapters. Metrology points in the form of laser tracker nests were attached to the load adapters at locations representing index feature locations in the full design.

Figure 10. Physical test setup

Laser tracker measurements were made of the shape of the fixture under this baseline load. Nominal spacers under the thermal growth rails were milled to account for the predicted and measured shape of the fixture beams to bring the interface planes to the nominal location as specified in the CAD model. This ensures the modular tooling, assembled offline, will be within adjustment range when installed in the fixture.

The result is a fixture ready to receive live loads.

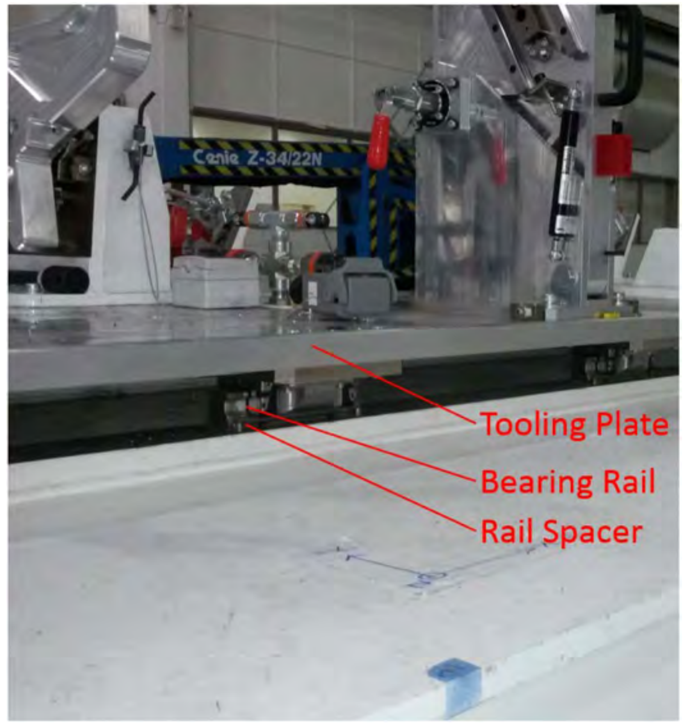


Figure 11. Interface plane spacers

VERIFICATION OF PERFORMANCE

Test Loads

Once the nominal, baseline, empty weighted shape of the assembled fixture was established, additional test weights were added representing the live loads of aircraft components. Other tests included:

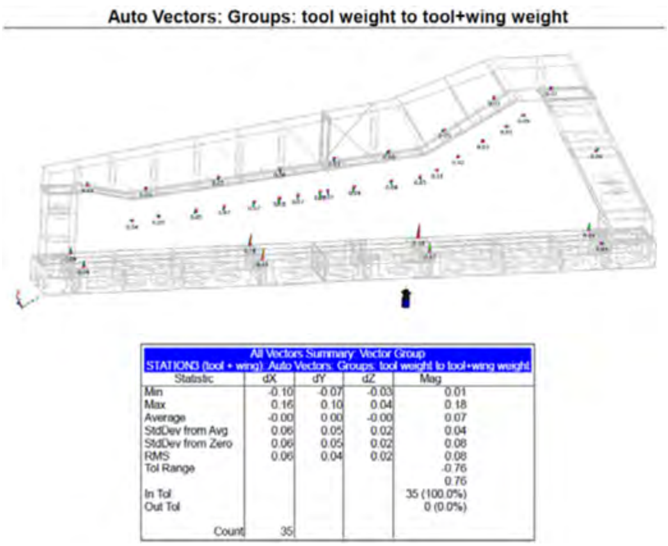
- Moving the frame along the floor rail system and back to the start point
- Lateral moves to the side and back
- Sensitivity of the system to rail deviations
- Lateral loads representing automated equipment pressure foot loads expected during drilling operations
- Dynamic loads for the specified number and weight of operators moving around in the fixture
- Uplift loads from the electric tug

Test Methods

The test method and data collection was straightforward. The locations of the metrology points at the tooling index locations was measured relative to the JRS before and after the test loads were applied. Deviation before and after load application can be compared directly to the predicted performance of the fixture.

Comparing Measured to Predicted Results

Spatial Analyzer software was used to examine the tracker data. A graphical representation of the data is helpful for visualizing the results while tabular data is good for comparing to predicted performance. Typical results are shown in the next Figures.



All Vectors Summary: Vector Group STATION3 (tool + wing): Auto Vectors: Groups: tool weight to tool+wing weight				
Statistic	dX	dY	dZ	Mag
Min	-0.10	-0.07	-0.03	0.01
Max	0.16	0.10	0.04	0.18
Average	-0.00	0.00	-0.00	0.07
StdDev from Avg	0.06	0.05	0.02	0.04
StdDev from Zero	0.06	0.05	0.02	0.08
RMS	0.06	0.04	0.02	0.08
Tol Range				-0.76
				0.76
In Tol				35 (100.0%)
Out Tol				0 (0.0%)
Count	35			

Figure 12. Spatial Analyzer results for the live load of loading the wing into the fixture (rear spar (top beam) weights only)

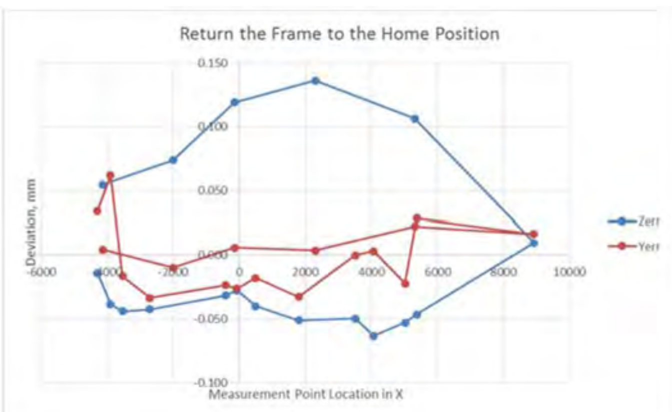


Figure 13. Measured index points of repeatability following a frame move 5m in X and returned to the home position.

Overall the measured results compares to predicted results within 10%. This is within the safety factor used in the design process. The load-holding capacity of the brakes to resist the applicable live loads was proven. Therefore the design process can be considered successful.

Table 1. Comparison of measured to predicted performance for a sample of loadcases.

Load Case	Predicted Deflection	Measured Deflection
Loading of Wing Components, Y deflection, upper beam	.068mm	.070mm
Rail Level Sensitivity, 3mm sag in the floor, Y deflection, lower beam	.185mm	.170mm

SUMMARY/CONCLUSIONS

Predicted and measured performance show a system can be designed to maintain required dimensional stability while moving a large fixture in the factory environment using low-precision rails.

The shape of the upper beam is a function of the section properties and span of the upper beam vs the live load of the aircraft components because its boundary conditions are not largely affected by the floor rail conditions. The shape of the lower beam is a function of the spring rate of the wheel suspension system vs the floor level and section properties of the lower beam vs the live load of the aircraft components.

At the expense of large changes in fixture level from one position to the next, a highly uneven floor could be accommodated by reduced spring rates in the suspension system.

Spanwise thermal growth differentials are minimized by the similarity in mass and heat-transfer rates of the wing components and the tooling baseplates which are not constrained to the steel fixture. This system has been shown to works well on similar assembly fixtures.

Over seasonal time periods, temperature changes in the factory are accommodated by the CTE match between the aluminum wing and the aluminum fixture towers in the chord-wise direction. Short-period thermal changes may cause a lag in thermal response proportional to the thermal mass and heat-transfer rate difference between the wing and the fixture towers. Minimizing these differences requires significant effort if large and fast temperature variations must be accommodated. Use of fans to force air through the towers can speed up the temperature equalization process.

A further development of this design and testing technique would be to graphically overlay the Spatial Analyzer result with the FEA analysis. This would enable quick visual correlation of the predicted and measured results.

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