Computer-Aided Inspection of Near-Net-Shape Turbine Disks

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A new ultrasonic inspection system, called CAUS-1, has been developed to inspect near-net-shape turbine disks. This system will maximize the cost benefits of turbine disks formed by near-net processing because it minimizes preform/inspection shape requirements. CAUS-1 has two new capabilities that have application beyond gas turbine disk inspection. Inherent in the system design is the ability to simultaneously dimension the part being ultrasonically inspected and to provide inspection data summaries for direct fabrication control. These capabilities offer cost saving advantages to applications where net or near-net shapes must be evaluated for material homogeneity and dimensional tolerance. These features are discussed in detail using a turbine disk inspection as an example.

Introduction

TRADITIONALLY, disks for gas turbine engines have high buy-to-fly ratios. New fabrication techniques, such as hot isostatic pressing (HIP) and isothermal forging, can produce disks that are close to final shape.[1] The use of these new processes will improve disk buy-to-fly ratio because they require less input material and machining.

The requirements of conventional inspection methods may limit the attainment of the full benefits of near-net processing. Typically, current inspection systems require inspection shapes to have machined rectilinear sides to enable the ultrasonic inspection beam to enter normal to the inspection surface. In addition, inspection shapes must be ⅛ to ¼ in. larger than the final disk shape to insure detection of defects within the final shape because ultrasonic instrumentation now in use has poor sensitivity to defects near the surface.

Besides ultrasonic requirements, there is concern that the small overstock on near-net shapes will require accurate preform measurements or dimension inspection to assure that the final shape can be successfully machined from the preform using standard fixturing. To minimize inspection constraints, an inspection system for near-net-shape disks must have the ability to contour sense and follow the inspection surface, if it is to automatically maintain the ultrasonic beam normal to the surface. This capability will permit the inspection and measurement of the unmachined nonrectilinear surfaces of the near-net-shape disks. The near-net-shape inspection system must also have the ability to detect defects near the surface and to reduce the overstock requirement. To facilitate final disk machining, the inspection system must accurately measure the preform shape. An inspection system, designed to meet the inspection requirements for near-net shapes, has been developed. This computer-aided ultrasonic system, called CAUS-1[2] (Fig. 1), uses new advanced ultrasonic instrumentation and transducers for improved inspection sensitivity and near surface resolution; it uses computer control to maintain transducers normal to the inspection surfaces. CAUS-1 has a software package designed to ease system operation, to provide shape dimension measurements, to input data into the CAM (computer-aided machining) system and to provide near-net-shape disk fabrication process control information.

With these capabilities CAUS-1 meets the inspection requirements of near-net-shape turbine disks. This paper focuses on two features of CAUS-1 which, because of their wide applicability, are of special interest. These are 1) the ability to dimensionally measure a shape simultaneous with an ultrasonic inspection of that shape and 2) the ability to prepare inspection data summaries that can be used to control fabrication processes.

Dimension Measurement

An important capability of CAUS-1 is its ability to adaptively contour-follow the surface under inspection. This capability is used to maintain the proper inspection geometry and is the means of collecting dimension information. Inspection surface contour is sensed by monitoring the ultrasonic energy reflected from the surface. Other surface sensing methods, such as eddy current sensing and peripheral transducers, were evaluated and were not found to be effective for disks where geometry can change abruptly. With the reflected energy method, the ultrasonic transducer can be maintained normal to the inspection surface to within 0.2 deg; this is sufficient for good inspection sensitivity.

The standoff distance (DOS) between the inspection surface and the transducer is measured using the time of flight of the

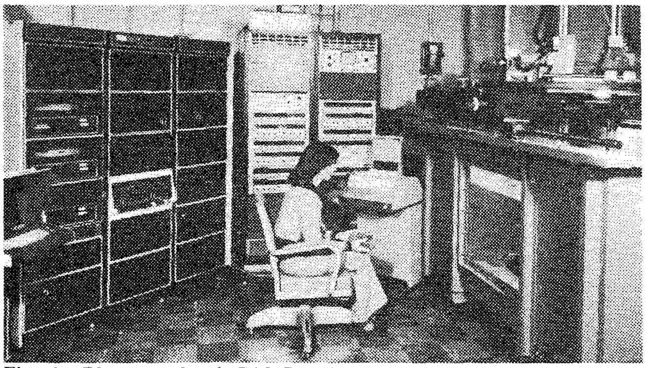

Fig. 1 Photograph of CAUS-1. The mechanical system is on the right, instrumentation and controllers are in the rear, and the minicomputer is on the left.

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ultrasonic pulse that is reflected from the disk surface. This distance is currently measured to within 0.0025 in. The speed at which the system can contour-follow is determined by the amount of variation in the surface. The limitations in scan speed occur because there is a physical limit to how fast an axis of motion can be moved. In CAUS-1 the rate controlling motion is transducer tilt, which has a maximum articulation speed of 10 deg/s. Figure 2 shows how the ability to scan wavy surfaces improves with an increase in this critical speed. When the worst-case preform surface variation is 0.040 in./in., the usable scan rate for CAUS-1 is 4 in./s; this is fast enough to give a fourfold improvement in inspection throughput over current methods.

CAUS-1 has 10 axes of motion under computer control (see Fig. 3). There are two transducers enabling simultaneous shear and longitudinal inspection techniques and detailed indication analysis. The high-tolerance mechanical components used in CAUS-1 have accuracies of ±0.001 in./ft for linear axes and ±0.1 deg for all rotational axes. The high-precision mechanical components permit accurate dimension inspection.

Each axis of motion is encoded with a digital encoder so its position can be continuously monitored. This position information, along with DOS, is collected and stored periodically at a predetermined rate or at predetermined positions. These data are joined to that taken from the second side of the disk and transformed into part coordinates using a special software routine. The second-side data are collected after the disk has been turned over; registry is maintained using special reference marks. Once collected and transformed, the disk dimension data are used as input to a computer-aided dimension inspection system, called CADI, which will be described in the following section. The accuracy of CAUS-1 dimension measuring capability was checked against a disk of known shape and size and is ±0.01 in. absolute and ±0.003 in. relative.

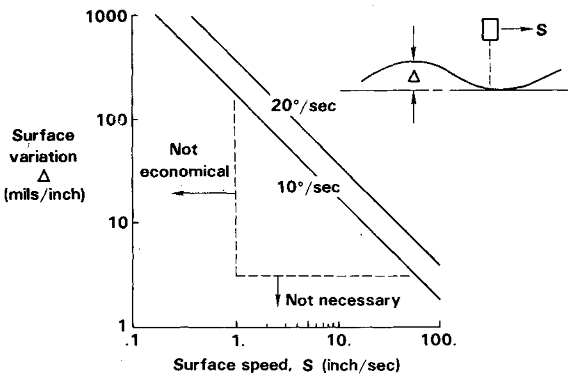

Fig. 2 A graph showing how the inspection scan speed is related to the waviness of the surface being followed. A scan speed limit is imposed because the transducers in CAUS-1 can be articulated at a maximum rate of 10 deg/s. A higher articulation speed of 20 deg/s would permit a given wavy surface to be contour-followed at a higher scan speed. The regions where the scan speed is too slow to be economic and where waviness is not sufficient to warrant contour-following are shown.

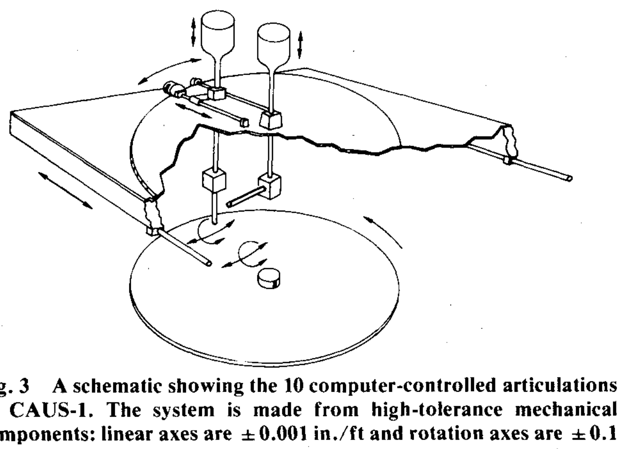

Fig. 3 A schematic showing the 10 computer-controlled articulations of CAUS-1. The system is made from high-tolerance mechanical components: linear axes are ±0.001 in./ft and rotation axes are ±0.1 deg. Two transducers are provided so that two inspection modes can be used simultaneously.

Computer-Aided Dimension Inspection

A software system called CADI (Computer-Aided Dimension Inspection) has been developed along with CAUS-1 to compare the three-dimensional disk shapes to the ideal preform or the final disk shape (CADI is designed to use data measured by CAUS-1 but it can use dimension data from any source). CADI indicates whether or not the desired disk can be machined from the preform using standard fixturing.

The dimension inspection is performed simply by comparing the perpendicular distance between the preform and the standard shape. This comparison is done using a larger and faster computer, such as an IBM 370, because of the large amount of data involved. Typically the number of coordinates necessary to describe the shape of a turbine disk with points on a ¼-in. mesh grid is in excess of 30,000. CADI presents inspection results either in the form of graphs such as Fig. 4, which show misfit in quantitative terms, or as interference diagrams that show qualitatively, in a plan view, where mismatch occurs.

When CADI finds that the standard fixture cannot be used, it has the additional capability to explore alternate setup of a specialized process plan. CADI does customized process planning, with human assistance, using a three-dimensional graphics display system that can present an isometric drawing of any three-dimensional shape consisting of a collection of points and/or lines. With the graphics system an operator can

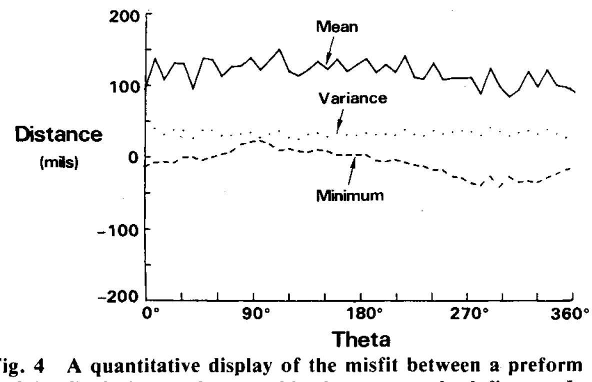

Fig. 4 A quantitative display of the misfit between a preform disk and its final shape when machined on a standard fixture. In this particular presentation the mean, variance about the mean, and the minimum misfit on a radial section disk are plotted as a function of the angular position of the section. The diagram shows that the particular part in question cannot be turned from the preform because the minimum misfit goes below zero.

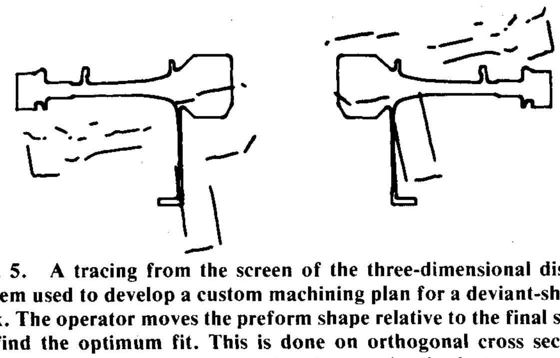

Fig. 5. A tracing from the screen of the three-dimensional display system used to develop a custom machining plan for a deviant-shaped disk. The operator moves the preform shape relative to the final shape to find the optimum fit. This is done on orthogonal cross sections before all cross sections are checked by rotating both shapes on the machine.

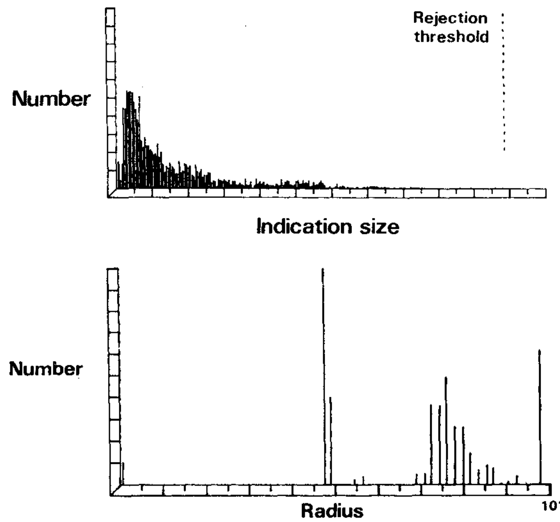

Fig. 6 Two presentations of indication density from the ultrasonic inspection of a disk. Process drift can be identified before parts are rejected by comparing these distributions with historical trends. The distribution of indications vs radial position on the disk is interesting because it suggests that the fabrication process is preferentially forming small non-rejectable indications at certain locations.

interactively tilt, rotate, or translate the shape, while the graphics system maintains the proper isometric display.

CADI presents to the operator on the graphic system the three-dimensional preform shape as measured by CAUS-1 along with the final shape. The operator simply moves one shape within the other until the best fit is identified (Fig. 5). CADI simplifies this task by providing the location of points of interference between the two shapes and statistical measures of local shape mismatch (Fig. 4). CADI automatically calculates the index set points necessary to assure that the preform can be machined to the final shape.

Fabrication Process Control

One of the most effective ways to assure that a fabrication process produces high-quality components is to institute detailed methods of process control. Traditionally, information such as rejection rate at various inspection steps have been used to give an indication of how well a particular process was functioning. With the advent of computerized inspection, there are new opportunities for improved process control. With a computerized inspection system, large amounts of detailed inspection information can be collected and used to give an insight into the state of the fabrication process. These data can be used to give a precursor warning that component quality is declining long before actual rejections occur. A special feature of CAUS-1 is that it can provide process control information for the material consolidation process and the shape forming process.

The ultrasonic response of a material is intimately related to the quality and internal structure of the material. Conventionally, the judgment of whether a material is acceptable is based on the absence of ultrasonic signals above a critical value. If rejection rates are low, there is little information available to evaluate whether or not the fabrication process is slowly changing. However, a computer-aided inspection system can monitor low rejection rate processes because, with its speed and storage capacity, it can record the presence of all indications, both above and below the critical level. The status of the process is indicated from a comparison of the data summaries for an individual unit to those of all previous units.

Figure 6 shows all of the ultrasonic indications above the noise level (all of these indications are smaller than the rejection level) found on the inspection of a disk, ordered into distributions showing the number of indications with size or number of indications with location. On the average, these distributions will remain constant from part to part as long as the process remains unchanged.

But, for example, if grain size or inclusion count were to change, a corresponding change would occur in the number vs indication size distribution. A change in the spatial distribution (e.g. the large density of indications at small radii in Fig. 6) might indicate the preferential formation of small forging defects in specific locations. The appearance of changes in the distribution of ultrasonic indications is a precursor warning that the process has changed, and if corrections are not made, there is increased likelihood that a rejectable indication will occur. This same type of process control analysis is available from the dimension inspection system in the form of summaries like Fig. 4. In this case, the variations in the shape of the preform due to die wear and other shape process variables are monitored. The integration of process control features into the near-net-shape inspection system will add to the advantages of near-net fabrication techniques for disks.

Conclusion

A computer-aided inspection system for near-net-shape turbine disks called CAUS-1 has been constructed and demonstrated. The system fully meets the ultrasonic inspection and shape measurement requirements of near-net-shape fabrication. Special features of the inspection system, the ability to check dimensions simultaneously with ultrasonic inspection and the ability to present inspection data for process status summaries, have application to fabrication processes where material quality and component shapes are evaluated, such as near-net-shape turbine disks.

Acknowledgments

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