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Digital manufacture of large-grade hydro turbine's blades

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ABSTRACT

The blade is one of the vital components and the most difficulty in manufacturing of large hydro turbines. In order to cost-effectively and productively manufacture these kinds of blades, a series of innovative digital techniques have been developed. It includes the digital design of hydro turbine blades based on manufacturers' requirements, computer-aided location and the machined error evaluation with three-dimensional digitized measure, tool path generation strategy for enhancing machining efficiency and controlling deviation in NC machining, tool path generation and NC machining simulation by means of a virtual NC machining environment for blades, and feasible strategy and the systematic scheme for manufacturing of large blades with 5-axis simultaneous CNC machining technology. The developed innovative digital manufacture techniques have been successfully applied in the manufacturing of both the large grade Kaplan and Francis hydraulic turbine blades. It has been shown that the higher efficiency and the better surfaces finish accuracy can be achieved in practical engineering.

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1. Introduction

Hydro turbine blades, such as Francis and Kaplan types, are usually designed by means of a series of special hydrodynamics methods, or digitized from the models. Traditionally, the large grade hydraulic turbine blades were machined by manual grinding operations and inspections with sets of the combined templates. The range of the deviation between the machined and designed model was usually within 1–1.5% D_1 (D_1 is the diameter of the runner, unit: mm) (Lai, 2000, 2001). If D_1 = 6000 mm, then the range of the deviation was 6–9 mm. This traditional way can neither satisfy the rapid developments of large hydro turbine nor ensure accuracy of finished blades. Hydro turbine manufacturers have been trying to machine these kinds of large blades using CNC machining techniques in recent year (Chen and Lai, 2003). For a Kaplan blade with runner's diameter of Ø6000 mm, it was machined by 3-axis simultaneous CNC machining technology with Ø100 mm ball-end cutter, if the scallop height was controlled less than 1 mm, the total machined time was about 210 h (Lai, 2000). As the surfaces of a large blade to be machined are usually from several to tens of square meters and involve bulk metal removal while machining from the blade's casting, it tends to be non-productive to machine these kinds of blade using traditional 3-axis machining with ball-end cutters. With the advent of large size multi-axis CNC machines, an innovative 5-axis simultaneous CNC machining technology has become not only feasible but also cost effective for large parts with sculptured surfaces. For the same Kaplan blade with runner's diameter of Ø6000 mm, it was machined by 5-axis simultaneous CNC machining technology with Ø200 mm indexable insert face milling cutter and a series of digital manufacture techniques described in this paper, if the scallop height was controlled less than 1 mm, the total machined time was about 30 h (Lai, 2001). As a large hydro turbine blade is closed with more than 10 sculptured surfaces that have irregular curvature distribution and very uneven thickness, so it is still much difficult to mill the blades by 5-axis CNC machining. In practice, the 5-axis CNC machining not only offers many advantages over the 3-axis machining, which include the higher productivity and improved surfaces finish accuracy, but also brings about more complex technological problems, such as highly complex algorithms for gouging avoidance and collision detection, complex surface machining errors that result from the traditional NC programming methods, etc. (Lo, 1999; Lai et al., 2003). However, a reasonable strategy and systematic scheme of blade's manufacture with the right combination of a series of digital manufacture techniques that we had developed can solve those complex problems in engineering and made them operational feasibility in technology. The developed digital manufacture techniques mainly include: (1) digital design and three-dimensional modeling of a blade based on manufacture's requirements; (2) computer-aided localization for position and setup by means of three-dimensional digitized measure for blades casting; (3) machining strategy and tool path planning with the help of computer-aided geometrical analysis; (4) 5-axis machining

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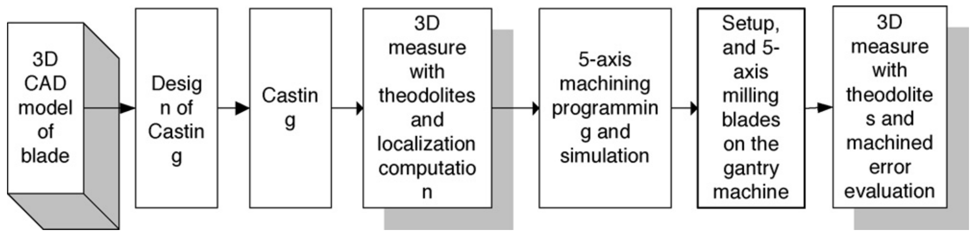

Fig. 1. A typical blade manufacturing strategy for large size hydro turbines.

tool path generation for different surfaces of a blade with Adaptive Step Length method and error control (Lai et al., 2003); (5) computer simulation for machining of a large blade to verify the cutting gouges and collisions between machine tool and blade and fixtures; (6) computer-aided inspection and the machined error evaluation for the finished blade surfaces by means of three-dimensional digitized measure; with the right combination of the above digital manufacture techniques, both Kaplan and Francis hydro turbine blades can be cost-effectively and productively manufactured, and it has been shown that the higher efficiency and the better surfaces finish accuracy can be achieved in the manufacturing of large blades.

2. Manufacturing strategy of large blades with digital manufacture techniques

The key to the cost effectiveness of 5-axis machining for large hydro turbine blades is how to make reasonable and feasible manufacture strategy and planning. By means of digital manufacture techniques that we have been developed, a typical blade's manufacturing strategy with 5-axis CNC machining is shown in Fig. 1.

3. Digital design for blade's manufacturing requirement

A hydro turbine blade is very complex body closed by sculptured surfaces. Conventionally, the pattern drawing is used to represent surfaces of blade in the runner's design, which is not able to meet the requirements for establishing digital models in the digital design and manufacturing of hydro turbine's blades (Lai and Wang, 1997; Lai, 2001). For the exact geometrical modeling of a blade, the pattern drawing has to be transformed to the point sets along the intersection curves between blade and stream surfaces with the special developed software (Lai and Wang, 1997), and then the NURBS representation is used as a unified digital model for the surfaces geometrical design of a blade. In order to implement NC machining on a gentry machine, a blade is usually subdivided into more than 10 sculptured surfaces (Lai, 2000, 2001). Fig. 2 shows a typical large Kaplan turbine blade, which consists of a flange with sphere surface and surfaces of face, back, inlet, outlet, hub and shroud with skirts. As shown in Fig. 3, a typical large Francis turbine blade can be subdivided into the surfaces of face, back, crown, band, inlet, outlet, weld preps between crown and blade, and weld preps between band and blade. How to establish the 3D model of these kinds of blade had been presented in the reference (Lai et al., 2002).

4. Localization and machined error evaluation by three-dimensional digitized measure

4.1. Three-dimensional digitized measure for blade's castings and finished blades

Each blade's casting has different and uneven stocks distribution. The castings are used to inspect 3D template in the traditional

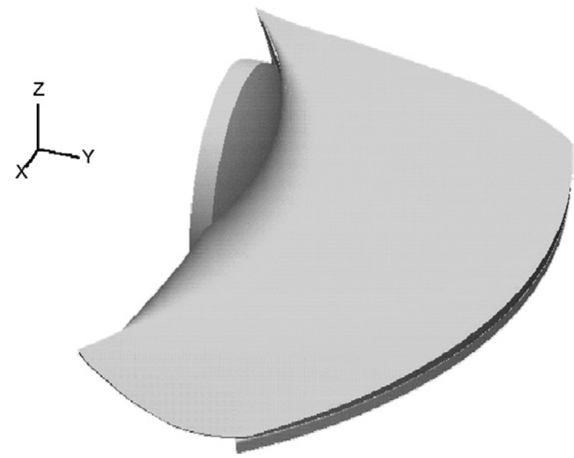

Fig. 2. 3D modeling of Kaplan turbine blade.

manufacturing technology (Chen and Lai, 2003), and the errors can be controlled under 1.5–2.0% D_1 (D_1 is the diameter of runner, unit: mm). The digital model of blade's casting cannot be defined by this way. However, the digital model of blade's casting has to be obtained in the digital manufacturing, so 3D digitized measure techniques is needed to inspect the blade's casting. After finished machining, the finished blades need to be inspected the compliance between the designed and machined, accordingly 3D digitized measure techniques is also needed. For each blade's casting or finished blade, a series of points on each surfaces of blade can be measured by non-contact or contact measuring methods (Lai et al., 2003; Sijie et al., 2004). The non-contact measuring instruments, such as high accuracy theodolites and laser tracker, are more convenient and suitable for large blade castings. Fig. 4 shows that a blade casting is being measured with the high accuracy theodolites (Made by Leica in

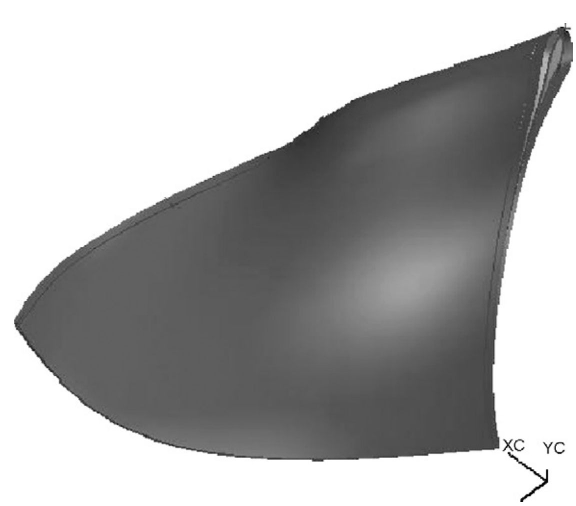

Fig. 3. 3D modeling of Francis turbine blade.

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