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October 2024

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Arabelle goes to new lengths

The two Arabelle steam turbine trains at Hinkley Point C in the UK, currently under construction, will each be capable of producing an astonishing 1770 MW (gross). A key contributor to this unprecedented power output is the deployment of 75in last stage blades in the Low Pressure (LP) modules, the longest such blades ever made. The size, coupled with strict limits on their weight, posed significant challenges for the development team, requiring new design tools and manufacturing processes. The result: a high performance last stage, manufacturable at moderate cost

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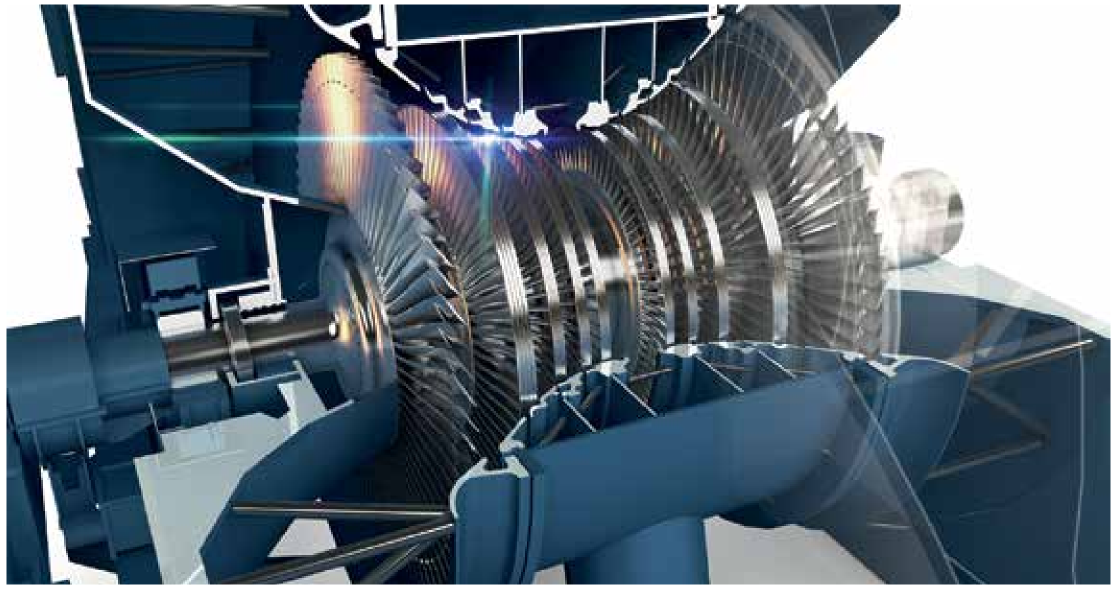
THE ARABELLE TURBINE PLATFORM HAS been developed for nuclear half speed applications and can be deployed with different reactor types and for different cooling water temperatures. Some typical PWR applications include Akkuyu in Turkiye, Flamanville in France, and Taishan in China. The Arabelle turbine trains for these power plants have a high-pressure (HP) and intermediate-pressure (IP) module as well as multiple low-pressure (LP) turbine modules. In the LP turbines, the last stage blades have a length of 69in (1.7526m). More recent applications have been identified that involve even lower cooling water temperatures and higher steam volume flows at the LP turbine exhaust. This has led to the development of a 75in (1.905m) last stage blade to accommodate the required increase in LP exhaust area. This increase in last stage blade length posed a significant challenge to the design team in the development process due to the strict limits on last stage blade weight.

Turbine configurations for nuclear plants

The main two categories of turbine configuration for nuclear power plants are referred to as half-speed (rotating at half of the grid frequency, 1500 RPM for a 50 Hz grid and 1800 RPM for a 60 Hz grid) and full speed (rotating at the grid frequency, 3000 RPM or 3600 RPM). Although there is a current trend to develop smaller reactors and full speed turbine designs, the economics of nuclear power plant design still require a high steam volume. A comparison of half-speed versus full-speed configurations for a given power plant output shows that the half speed layout involves a reduced number of LP turbine modules and a requirement for only one train, whereas at large power outputs the full-speed layout requires two trains. Clearly these are not the only considerations when designing the plant, and the plant economics vary over time and depend on the geographic location and power market. Nonetheless, the half speed train configuration remains the most cost-competitive solution for very large powers, when one considers only the cost of the turbine train itself.



Above: **Rendering of Arabelle LP module** Source: Arabelle Solutions

Above: **Lift of Arabelle LP rotor at Belfort factory** Source: Arabelle Solutions

A solution for Hinkley Point C

As countries transition away from fossil fuel-fired power plants to alternatives, many have chosen to extend or replace their nuclear power plant fleet. In the UK, it was decided to build a new nuclear power plant next to the existing one at Hinkley Point B near Bridgwater in Somerset on the Bristol channel, as this latter plant was coming to the end of its operational life.

The first new nuclear power plant in the UK in a generation, the requirement was for a large power output, over 3 GW, for which the Arabelle turbine is well suited.

The cooling water temperature at the Hinkley Point site is relatively low compared to existing Arabelle turbine applications. For improved performance and higher power output, the turbine design team at Arabelle Solutions needed to increase the last stage blade exhaust area by increasing the last stage blade length from 69 inches to 75 inches (1.7526 to 1.905m). The two turbine trains, as finally designed, can produce 1770 MW each (gross).

To compare the length of steam turbine last stage blades, in terms of the stresses in the blade roots and airfoils, as well as how challenging they are to design, one could scale them geometrically so they operate at the same rotational speed. If this is done, it becomes clear that the last stage blades employed in steam turbines deployed in combined cycle and coal-fired plants are significantly longer than those typical in the nuclear market.

Combined cycle/coal applications are predominantly full speed and the lengths of steel last stage blades used for large full speed combined cycle/coal plants range up to 48-50in at 50 Hz (1.2192-1.270m). If one were to scale a nuclear half speed blade to full speed (25 Hz to 50 Hz), for example a 69in (1.7526m) blade, its length would be around 35in (0.8890m), well within the design space envelope of existing full speed last stage blade designs.

Because the length of the last stage blade required for Hinkley Point C would be similar to that already developed for full speed last stage blade applications, the design team could have simply taken a last stage blade developed for full speed applications and scaled it by a geometric scaling factor of two for the new application.

However, whilst the aerodynamics and thermodynamics of the layout would remain similar, given that the rotational speed is also scaled by the inverse of the geometrical scaling factor, other parameters scale differently. The turbine mass flow and machine power scales by a factor of 4 – this is an advantage of the half-speed configuration. The last stage blade weight scales by a factor of 8. This increase in blade weight would require extremely large bearing pedestals to contain the rotor in the event of a last stage blade failure and would potentially result in a large missile if a blade failed and escaped the casing.

The restriction on airfoil weight is one of the biggest challenges in the development of the low-pressure turbine for half speed applications: that is keeping the blade mass to a minimum, whilst maintaining a blade stiffness that avoids aeromechanical excitation, and ensuring the blade can be manufactured in a repeatable and cost-effective manner. The scaling of other turbine components from full speed to half speed can also lead to a sub-optimal solution. There are limits on the physical size of the inner casing and outer casing in terms of transport by road and rail. The bladed rotor also needs to fit inside the “spin pit” bunker (the spin pit being an evacuated chamber used for testing). Other components would also have an excessive weight, if simply scaled from a full-speed application.

A new last stage blade for Arabelle

The last stage blade for the LP module of the Arabelle turbine platform consists of three main elements: a fir tree root; an airfoil; and a snubber. The blade airfoil geometry is represented by a series of profile sections and these are initially designed by the aerodynamic designer, then can be further modified in the downstream design processes.

Above: **CAD model of the 75in (1.905m) LSB** Source: Arabelle Solutions

Due to the requirement for a very light blade with thin profile sections, a different frequency tuning strategy needed to be developed for this particular design. Many more airfoil design sections were required to enable more local changes, to allow the designer to more easily influence the complex mode shapes of the higher modes and tune their frequencies.

The performance of the LP flowpath is highly sensitive to the shape of the airfoils of the last stages. For this reason, an integrated design system was applied that focuses on achieving high aerodynamic performance, whilst also considering the requirements of other design aspects, such as mechanical integrity and ease of manufacturing. The assessment methods for the non-aerodynamic aspects in the design system are of lower fidelity than used in the mechanical integrity and design disciplines, however it enables a more efficient design development because there are fewer design iterations needed to achieve the product requirements.

In order to have a sufficiently stiff last stage blade, the aerodynamics layout was adapted to increase airfoil camber. Local changes in the section area, and profile shape to influence the bending and torsional stiffness of the profile over the blade height have been applied to tune the higher modes. In other designs, the geometry has been modified after the aerodynamic design was complete, through changes to the airfoil surface, to achieve the required frequency layout. In the Hinkley Point C design process, this has been avoided largely due to the application of the integrated design system. This enabled a much higher aerodynamic performance than would have been possible with a less integrated design process.

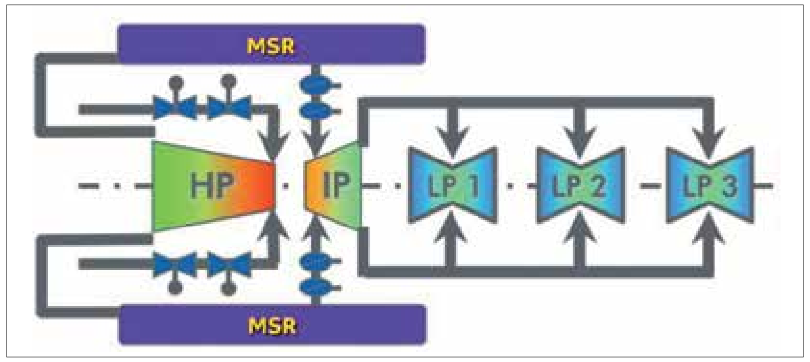
An important aspect of the last stage blade development was the understanding of the influence on the frequency behaviour of geometric variations generated during the manufacturing process. This was carefully assessed using finite element (FE) simulations. The geometry was modified through a morphing process. A specific strategy for machining was also developed. Additionally, FE simulations have been used to anticipate the deflection of the blade during the machining process.

Adaptations to the manufacturing process

Usually, large last stage turbine blades are milled in a horizontal position, with each end fixed. The machining of relatively big and slender blades poses some challenges due to the flexibility of the airfoil in the region far from the support where the blade is clamped. In this configuration, the mid span region of the blade is where the blade experiences the maximum deflection due to the force of the milling tool. The longer the blade, the larger the deflection for a comparable machining tool force. Experience in machining blades of smaller size, for example the 69in (1.7526m) last stage blade, highlighted the need to define a dedicated machining strategy to ensure a better control of the geometrical deviation on the airfoil for even longer blades. This included collaborating with the milling machine manufacturer to improve the milling machine for this type of blade design.

To address the relatively large variation in geometry in important regions of the airfoil, which led to a significant and undesirable change of the blade natural frequencies, two strategies were used. The first was the application of a blade milling machine equipped with an additional support in the middle of the airfoil. The second was the introduction of a specific feedback process to ensure quality control during manufacturing. All the blades have been automatically measured in many control sections distributed along the airfoil with a co-ordinate measuring machine (CMM). The aggregate results of these measurements were used to improve the design definition, to reduce the sensitivity of the design to manufacturing variations.

The first blades machined, before starting the actual series production, have been assessed in respect to the natural frequencies considering the average deviation measured in each section. The contribution of each individual section was calculated with a finite element analysis and the frequency impact estimated by superposition. The specification of where to correct the milling program was provided, identifying the region where to aim for a thicker or thinner profile to ensure that the machined geometry was less sensitive in terms of the resultant blade frequency. After a number of iterations, once a satisfactory manufactured geometry was obtained, during the series production the machined geometry was constantly monitored to ensure an acceptable natural frequency behaviour. The first two blade rows have been tested assembled in the rotor and rotated in the spin pit. In the tests, strain gauges were applied to the blade surface and the blades are excited through the use of an air jet impinging on the blades to measure the natural frequencies. The correct frequency behaviour of the manufactured blading was confirmed.



Above: **Schematic of the Arabelle turbine island with the moisture separator reheater (MSR)** Source: Arabelle Solutions

Validating for operation

Due to their large size, and low natural (structural) frequency, last stage steam turbine blades can be subject to aeromechanical effects. This is where the unsteady flow interacts with the vibration mode shape to increase the blade vibration amplitude, sometimes to unacceptable amplitudes. There are two main categories of aeromechanical interaction, one self-excited where the vibration itself creates an unsteady force in the flow which is known as flutter, and a forced response-type excitation where the unsteadiness is generated by the flow conditions only. Forced response may be due to stochastic unsteadiness such as flow turbulence, or at off-design conditions there is also a rotating stall type phenomenon, where the blade is stalled, and rotating stall cells produce an unsteady force and consequently blade vibration. To validate for these phenomena, a test turbine or on-site tests are required. For the new 75in (1.905m) last stages of the HInkley Point C LP module, a scale turbine model was manufactured, and a thorough testing campaign was undertaken across the whole operating map. Even at conditions well beyond typical applications, the measured amplitudes were significantly below the dynamic stress limits imposed by the design rules. The tests were used to confirm the applicability of the last stage blade protection diagram, which is used by the operator to ensure that the last stage blade is operating within the correct regime.

Above: **HPCs eight steam generators will drive the two giant Arabelle turbines at the plant**

A new blade for a new generation

Efficient cost-effective turbines for very large nuclear applications require very large last stage blades. For the Hinkley Point C development, the size of the last stage blade, and the requirement for a relatively low blade weight posed a great challenge for almost all aspects of the design and development process. Unlike typical design projects, these constraints led to the development of new development processes and tools.

In summary, the following aspects played a key role in the development process:

- **Improvement of the design system:** Enabled the aero designer to implement the frequency and stress layout strategy from the mechanical integrity designer, with less iteration and enabling the achievement of higher performance. The consistency in geometrical modelling between the mechanical design, aerodynamics and mechanical integrity analysis avoided errors and the requirement for additional design iterations.
- **Frequency layout process:** The complex tuning process of the mode shapes of the last stage blade was facilitated by changes to the design system, as well as the consistency of the geometry in the different disciplines and analyses.
- **Design for manufacturing:** Detailed understanding through measurement feedback of the geometrical variations in the manufacturing of the blade airfoil allowed adaptation of the manufacturing process, the milling machine, the tolerance scheme, and the geometry itself to achieve the requirements in terms of mode shape frequency layout and stresses.
- **Validation:** Scaled turbine testing over the whole operating map of the turbine ensured that the last stage blade can be operated even in off design conditions, as no aeromechanical issues were identified.

The development and application of the design tools and new manufacturing processes led to the creation of a high-performance last stage which could be manufactured at moderate cost. The increase in exhaust area of the last stage compared to the previous 69in (1.7526m) design has enabled a significant increase in the power plant output of the Arabelle steam turbine train, with the first units currently being deployed at the Hinkley Point C power plant, in the UK. ■