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Conference Paper · June 2016

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Digital Design and Ergonomics Assembly Process Simulation of Conveying Equipment in Electric Generator Manufacturing

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ABSTRACT

A manufacturing enterprise is concerning about conveying equipment design and work station layout design in generator stator winding assembly due to the huge size, heavy weight of stator coils and the limitation of workshop space. This work used mechanical theory and kinematic simulation to achieve the conveying equipment design by simulation software, and determined the work station layout and dimensions by using the ergonomic analyses, such as OWAS analysis, reachability and visibility analysis. The analysis results are used to evaluate the welding feasibility of generator base and spring plates. Such a procedure can be generally applied to different heavy equipment manufacturing companies.

1. INTRODUCTION

In the large electricity generator manufacturing industry, the coil conveying equipment has put into use for stator winding assembly. Hence, it is necessary to carry out the work station layout design and ergonomic analyses for such manufacturing process. However, in a long time up to today, such heavy product manufacturing like the assembly sequence, or the path of coils, relied on the personal experience, lacking of the effective measures of pre-verification. Due to the heavy weight of coils, the coil conveying equipment (namely the special coil lifting handling equipment) is used in the winding process of generator stator assembly to install the stator coil into stator inner cavity. However, the huge length of the coil and the strict stator inner cavity dimensions create tight constraint for the coil motion path. In the process of assembly, it is often that the interference between stator cavity and coil occurs. To avoid the interference, workers often need to adjust the coil conveying path by themselves manually. As a result, it causes a lot of non-value-adding labor, wasted time, and inefficiency. Of course, the workshop space is always a restriction. Further the process engineers must consider the welding operation for the generator base and spring plates from the ergonomic perspective. A variety of studies have been conducted on ergonomics for manufacturing industry. The use of participatory ergonomics has resulted in re-designs of the new product, which improved the efficiency and ergonomics of the assembly operations [1]. The ergonomics analyses are currently applied broadly in design, modification, visualization and analysis of human workplace layouts and/or product interactions [2-12]. However, for large electricity generator assembly, little information is available about the equipment and work station layout simulation as well as ergonomic and kinematic analyses, even though the computer 3D simulation technology has been available for the manufacturing industry. Considerations for this aspect are still experience based. Hence, the work station layout design innovation is necessary for the large electricity generator assembly process.

Conducting kinematic and ergonomic simulations of complex equipment/fixture and ergonomic analysis under 3D virtual environment has become a trend in the manufacturing industry because such analyses have manifested their own values. The outstanding advantages of prior simulation are both economical and practical. For example, the technology can check the feasibility of the equipment movement, i.e. accessibility, interference, synergetic coordination between equipment and equipment, interactions between equipment and human, etc. Due to the ability of finding the design errors of equipment/fixture before the product manufacture is put into action, it can improve productivity and reduce

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the manufacturing cost greatly. In this work, computer virtual three dimension (3D) simulation method has been used to verify the feasibility, rationality, correctness of manufacturing processes and to optimize the conveying equipment design as well as the work station layout design before the actual manufacturing process. Digital models are applied in the dynamic simulation of the assembly process for generator manufacturing and the ergonomic analyses of assembly/welding processes. The involved evaluations include Ovako Working posture Analysis System (OWAS) analysis, reachability and visibility analysis, and so on. This method can avoid the costly physical verification and improve the efficiency of research and new product development efficiency. The implementation of this study proves that the integrated technology can effectively improve assembly quality, reduce manufacturing cost, and shorten the product development cycle. It also provides a pilot application example for heavy product manufacturing industry.

2. BACKGROUND AND METHODS

2.1. BACKGROUND

The large electricity generator is the typical complex product. The generator stator has two-layer windings with 84 coils. Each layer winding is divided into groups and each of them is different in length and weight. In the process and manufacturing department, a conveying equipment system has been used and it has to be customized. The conveying equipment redesign for each new product is also the daily work of the manufacturing enterprise. This study covers conveying equipment design and ergonomic analysis in work station layout for stator assembly/welding process. In this section, the key mechanical theory and kinematic simulation methods for the equipment design are briefly introduced. They are used to verify whether the coil motion path is reasonable or not in the assembly process. As the limitation of work space height, the layout design of generator frame support device and work platform above the ground should not reach too high. We also used the 3D human model with medium Chinese male build to verify the rationality of layout in NX (Siemens PLM Software), a virtual simulation environment. In the welding feasibility analysis, a 3D human model and a welding gun model were created in NX and some related ergonomic analysis was implemented. Three key aspects are reported here: stator coils conveying equipment design; ergonomic analysis for welding; and work station layout design for assembly/manufacture. The authors accomplished the conveying equipment design via kinematics modeling and simulation. On the other hand, the work station layout design and welding feasibility were completed by using the simulation results of ergonomic analysis. The involved research activities can be clustered into three main phases: 1) data collection phase, 2) modeling phase, and 3) validation phase.

2.2. Data collection phase

As the first phase, the authors collected all the data needed for the simulation model development, including the 3D models of the electricity generator, conveying equipment and other necessary tools. Beyond that, the data about the shop floor plant layout and the process parameters of each work station is also collected. Those 3D models mainly came in the form of 3D CAD software, in this case, NX part files. In addition, the authors also collected data and information about shop floor operators' characteristics, e.g. age, gender, height, weight and physical condition, tools' (equipment's) dimensions (length, width and height), and so on. Operators' characteristics were used for selecting human models capable of representing the real workers as much as possible. Simulation results of kinematics and ergonomics were used for determining the geometric dimensions of each work station design.

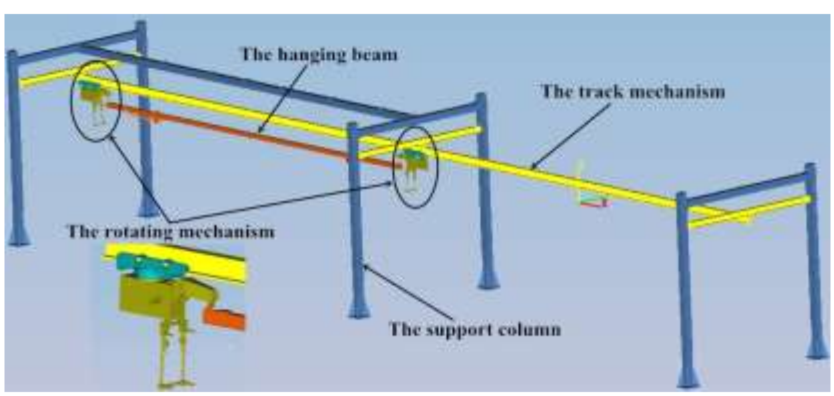

Figure 1: The structure of the conveying equipment.

2.3 Modeling phase

After the data collection phase, the second phase is the construction of conveying equipment kinematics model and the work station simulation model. The authors use NX [13] and Tecnomatix [14] for developing the 3D geometric model and kinematic model. This phase involves two different steps: (1) The creation of three-dimensional geometric models of virtual environment and tools used during the manufacturing process; (2) Kinematic modeling for conveying equipment and human model insertion into the virtual environment. The structure of the conveying equipment is shown in Fig. 1. The rotating mechanism of the equipment could slide forward or backward along the track. At the same time, it also could perform rotational motion about its vertical axis. In the process of electricity generator stator assembly, firstly, the workers adjusted the rotation angle of the rotating mechanism by trail and error, and then they pushed it forward (the rotation angle of rotating mechanism may change a few times during the assembly process if necessary). The coils were hanged on the hanging beam and delivered into the stator inner cavity when the rotating mechanisms were sliding on the track.

In the process of kinematic modeling for conveying equipment [16], the authors used basic linkage group theory of mechanism. Any mechanism consists of three parts, which are frame, original motive parts and follower systems. The constraint conditions that a mechanism has determine the movements. The number of the motive parts is equal to the number of DOF (degrees of freedom), as a result, if we separate the frame and the original motive parts which is connected with frame from follower systems, then the DOF of rest follower systems was 0. Sometimes the follower systems can be decomposed into several simpler component group with 0 DOF. Such most simple components group which cannot be subdivided no longer and with 0 DOF, we call it basic *linkage group*, or Assur's group. Any mechanism can be regarded as composing of several basic linkage groups, each group connecting to the original motive parts and frame system. The basic rules described so far is referred to as the composing principle of mechanism.

Table 1: Three basic concepts of mechanism

Mechanism	Mechanism is a system that can translate one or a few rigid mechanical movement into other specific rigid mechanical movement, and the determined movement between each unit (link) is connected by kinematic pair.
Link	Link is the movement unit of mechanism, and it consist of part/component without relative movement.
Kinematic Pair	Kinematic pair is the movable connection formed by two components which direct contact with each other, and it provides limited relative motion between components under the constraint.

According to the above definition of mechanism, a mechanism can be composed of multiple component objects and mutual connections (kinematic pair objects). When we analyze the mechanical movement, no matter how complex a planar linkage mechanism is, without exception, it consist of the basic components such as linkage, slider, and basic linkage group. We can implement kinematics modeling in the software based on the composing principle.

2.4 Validation phase

2.4.1 Kinematics simulation of conveying equipment

To verify whether an assembly task can be completed or not by using the conveying equipment, the interference checking needs to be enabled simultaneously in the Tecnomatix system. Under the *Kinematics Module* of Tecnomatix software, the tasks of modeling include connections creation for each link and joint kinematics functions editing. Finally, for the generator assembly using such conveying equipment, we could get its kinematic path and operational approach after the simulation work. Fig. 2 (a, b) shows the general view of coil's assembly by using the conveying equipment. The coil is fixed on the hanging beam while the conveying equipment is used in the operating process. According to the results of the simulation, the movement path of conveying equipment could show as connection of each "pose" (Fig. 2 (c)). For the implementation of structure design and validation of conveying equipment, the key dimensions of conveying equipment need to be determined case by case. The concept of assembly features is applied here [17, 18]. For each case, the kinematic changes of each revolute joint and prismatic joint have specific values, so it ensures the customized simulation results.

2.4.2 Ergonomic analysis and work station layout design

In the process of the large generator assembly, ergonomic analysis is necessary to evaluate whether the work station layout design is reasonable or not. The main characteristics of human model are 175cm (height) and 79kg (weight), which are typical for Chinese workers. The evaluation of characteristic parameters can lead to the reasonable work access conditions, such as the reasonable height of working platform and the flexible orientation of coil towards generator stator so that workers can easily complete assembly operation. Besides, in the base and spring plate welding process, reachability and visibility analysis should be implemented. Tab. 2 shows the contents of the ergonomic analyses [10,15].

(a) (b) (c)

Figure 2: Assembly process of generator stator coils by using designed conveying equipment.
(a) The scene of coil's assembly by using the conveying equipment, (b) The axial view of the generator stator in the assembly process, and (c) The kinematic value of the each revolute joint and prismatic joint for conveying equipment.

Table 2: The contents of the ergonomic analysis.

Ergonomics requirement	Definition	Test method
Analysis of body postures	A quantitative analysis of body postures and effects on the musculoskeletal system.	Simulation with Tecnomatix/Jack, use the analysis module (OWAS).
Reachability analysis	The workers should reach and easily operate the operation object with hands or tools.	Test on software to identify operation distances and examine the maximal grasp scope.
Visibility analysis	Make ensure that the field vision of the workers in the (welding) operation.	Simulation with Tecnomatix/Jack, use the vision module in the programmer to get a field of vision.

3. RESULTS

3.1. CONVEYING EQUIPMENT DESIGN

3.1.1 Kinematic modeling for conveying equipment

Cyclically, work station layout design and conveying equipment design are associated. For example, the feasibility validation of work station layout must be supported based on the result of conveying equipment and human factor analysis. Note that although the conveying equipment contains flexible belts on the hanging beam, they are the vertical structure and the speed of equipment is also smaller. In this case, the conveying equipment still belongs to the planar linkage mechanism. Applying the aforementioned mechanism modeling method, we classified each link and created joint for them, then completed the kinematic modeling for conveying equipment in the simulation software (Fig. 3).

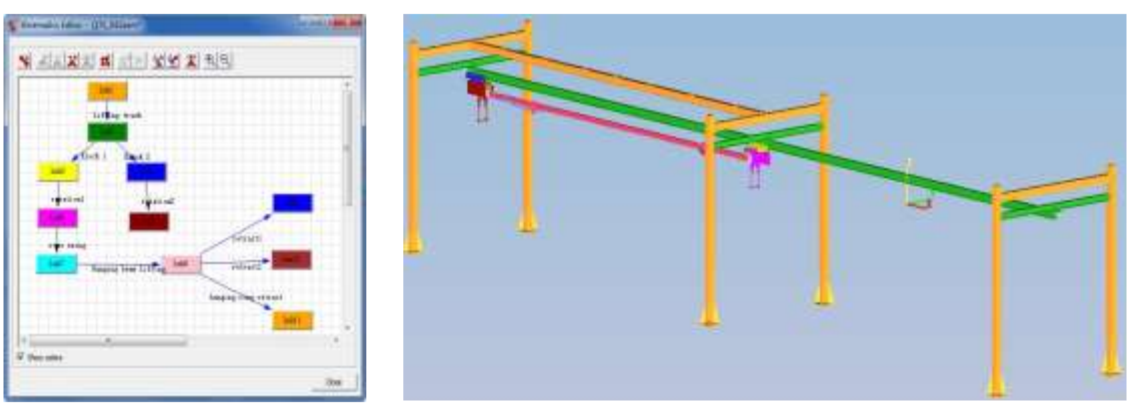

Figure 3: The result of kinematic modeling for conveying equipment and corresponding mechanical structure for each link.

3.1.2 The result of conveying equipment design

Ideally, the consideration was that the stator coils could easily enter into the stator without any interference when we used such conveying equipment. In addition, the rotation angle of rotating mechanism arm could not exceed ±90 degrees. The simulation results showed that the radius of rotating mechanism arm was the key dimension factor in the assembly process. In fact, when the radius uses the original design dimension value, the conveying equipment interferences the assembly process. The key dimensions of the conveying equipment have the significant effects on generator assembly, they are: (1) The radius of rotating mechanism arm; (2) The length of track mechanism.

3.2. ERGONOMIC ANALYSIS AND WORK STATION LAYOUT DESIGN FOR GENERATOR ASSEMBLY

(1) The ergonomic simulation and analysis

Firstly, we accomplished the initial work station layout design. We use ergonomic method to verify whether it was practicable or not for workers to perform operations. For example, we attempted to make sure that the height of working platform and steps was applicable or not in the assembly process. Fig. 4 and Fig. 5 showed the results of a simulation analysis result, and the information that we could obtain from the simulation results was OWAS reports.

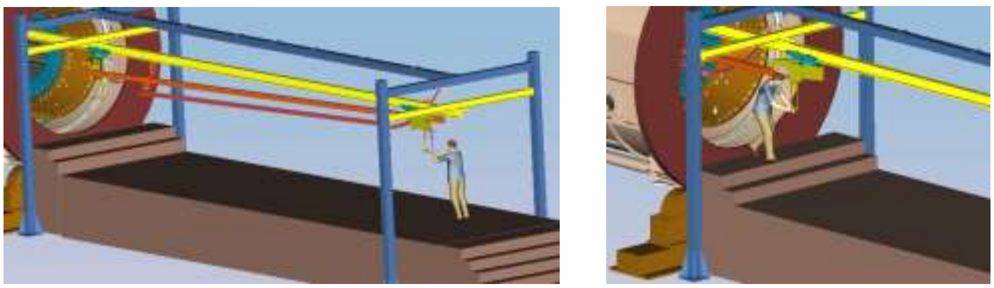

Figure 4: Shop floor worker operates the conveying equipment in the virtual simulation environment.

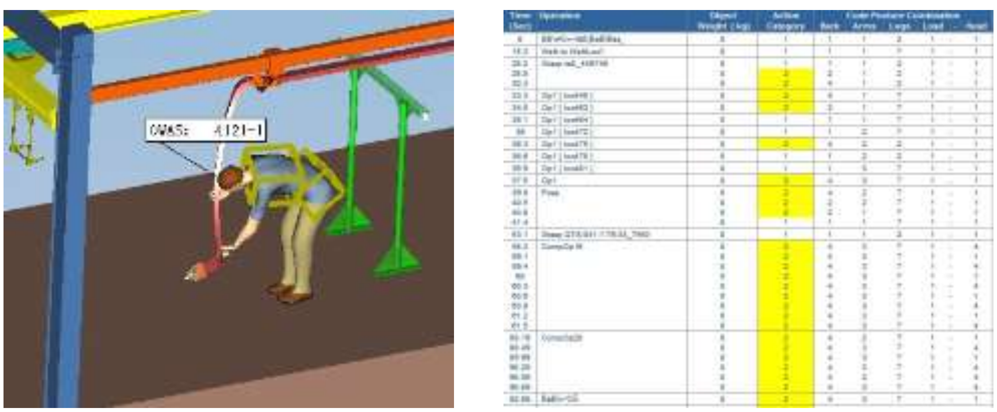

Figure 5: Part of OWAS analysis results for generator assembly operation

(2) Work station layout design (see Tab. 3)

Table. 3: Work station layout design of generator assembly.

The height of working platform	≥1.38m
The height of working step	1.85m
The height of support frame	1.50m
The width of working platform	≥3.50m
Generator stator layout	Distance from the ground 1.19m
The roller support equipment layout	Apart from each other ≥9.36m
The layout for global work station	length≥27.33m; width≥5.55m; height≥5.81m

Layouts of work station are also showed in Fig. 8. The support frame of coils is 1.50m high and working platform is 3.50m wide. The roller support equipment layout 9.36m apart from each other. Fig. 6 shows the layout of global assembly work station. In other words, it stands for the minimum sizes of workspace requirements.

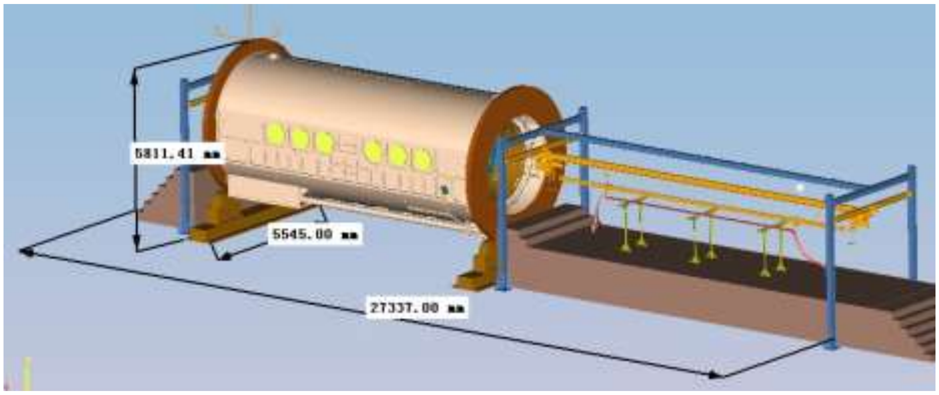

Figure 6: The layout for global work station.

3.3. WELDING FEASIBILITY ANALYSIS AND LAYOUT DESIGN

For the lateral spring plate welding, engineer manipulated the 3D human model enable pass through the inner walls of plate hole, then the 3D workers model would be used to simulate welding operations. By applying the visual function at the same time, we got the first perspective of the operations to determine whether the position of welding operation is feasible and comfortable or not. According to the height of standard human body model (175cm), this work platform height (human feet z-axis) is consistent with the height (z-axis) of bottom of generator stator base. On such welding operation platform, we assured that the workers could not only easily reach the deepest welding seam with specified welding gun but also remain visible on welding position (Fig. 7).

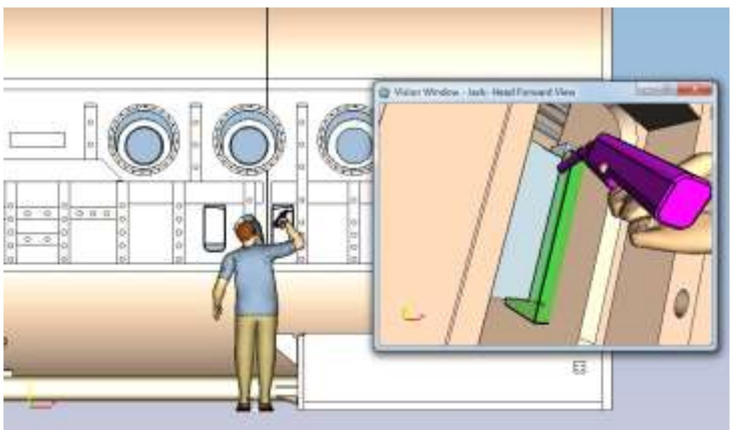

Figure 7: The welding operation for lateral spring plate.

4. DISCUSSION AND SUMMARY

4.1. RESULT CONSIDERATION

Based on the authors' investigation about the generator stator coil insertion, the current height (1.38m) of working platform, shop floor workers can easily complete operations (rotate and push the rotating mechanism arm) of the conveying equipment. Therefore, in the actual assembly process design, we need to provide a set of apparatuses matching with such a layout. However, it was discovered that the current work station layout still has a limitation, i.e. workers have to put aside support frame of coils before each coil is transported into the stator inner cavity. It causes inconvenience in an actual assembly because of the existence of this working platform. Therefore, it was suggested that the whole stator and the roller support equipment should be built under the working ground. On the basis of this existing layout, the whole stator and roller support equipment can be arranged to descend 1.38m (correspondingly, track beam should fall 1.38m), meanwhile the foundation bolt of conveying equipment is still fixed on the ground. In such a way, the rising working platform is no longer needed, and the new layout will bring much convenience for the coils assembly operations.

As to be seen from the case study above, the coils conveying equipment design is the key for the generator assembly process. Generally, this costly equipment is purchased from original equipment manufacturers (OEMs) based on the traditional manual assembly. Therefore, the availability of coils conveying equipment is very important when the enterprises are manufacturing different models of products. At this point, it requires improvement or redesign of the coils conveying equipment by changing structures or parameters. The ergonomic analysis of generator assembly and welding process offered us the guidance to design the work station layout and to evaluate the operational requirements/suggestions before it's actually used for production.

4.2. SUMMARY

3D simulation technology has used to complex equipment/fixture and ergonomic analysis under the virtual environment and it has become a trend in the manufacturing industry through its unique values. In the case study conducted in a heavy equipment manufacturing industry, engineer could avoid the costly physical verification through the application of virtual simulation technology. The advantage of prior assembly simulation is that the design errors of product/equipment can be found before production is put into action, so it helps manufacturing enterprise to avoid the costly physical modifications, reduce production costs, and improve the efficiency of new product development.

5. CONCLUSIONS

This paper presents a case study of an assembly workstation design with the supporting conveying equipment design and ergonomics analysis for large electricity generator manufacturing industry. Through 3D simulation software, the authors completed the kinematic modeling and simulation of conveying equipment, then the result of equipment design was given and kinematic paths/operational approaches of conveying equipment were provided based on the simulation work. The authors determined the work station design dimensions and layout of assembly process by using of the ergonomic analysis method. In the welding process of generator base and spring plates, we estimated the welding feasibility and completed layout planning by using the results of ergonomic analyses (OWAS analysis, reachability and visibility analysis). Application of computer virtual 3D simulation methods were used to verify the feasibility/rationality of manufacturing process and the conveying equipment and work station layout was optimized before the actual manufacturing process. In consequence, the proven procedure can avoid the costly physical modification, error-fixing and hence improve the research and development efficiency for generator manufacturing enterprise.

ACKNOWLEDGEMENTS

The authors would like to acknowledge financial supports of National High-tech R&D Program of China (2007AA040503), and the 111 Project Grant (B13044) of NPU, and the support by Key Lab of Contemporary Design and Integrated Manufacturing Technology, Ministry of Education in China.

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