Development and application of CATIA-based interference simulation system for tube bending

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Abstract. Aiming at the urgent demands for precise and intelligent forming of complex bent tubular components, this paper reviews the developments of tube bending related simulation technologies. Combined with the advantages of finite element (FE) simulation analysis and geometry motion simulation analysis, the present work is proposed to establish a knowledge base of tube bending simulation based on the knowledge engineering technology, and to develop an interference simulation system of tube bending based on CATIA software. Through the application of interference simulation system in continuous tube multi-bending in civil aircrafts, the extraction of model data, selection of process parameters, FE simulation of single bending segment, geometry simulation of continuous multi-bending, generation of simulation reports and numerical control codes can be automatically realized, and the bending quality and interference situation can be simultaneously obtained. Using the interference simulation system, the product efficiency of aircraft duct components can be greatly improved, and the labour cost and working intensity of technicians can be significantly reduced.

1. Introduction

To meet the increasing demand for passenger transportation in the civil aviation field, the frequency of aircraft replacement is getting faster and faster, which requires shorter and shorter design cycles, and a highly parallel design/manufacturing process. Aircraft design process has been transformed from the traditional patterns to a highly integrated patterns of digital design-manufacturing. Product model information is no longer confined to the traditional physical model, but also contains a large amount of processing information. The approaches, carriers, and expressions for acquainting process information have also experienced significant changes. Design/manufacture processes have transformed from the two-dimensional drawings to the three-dimensional information and three-dimensional models. Digital and intelligent design/manufacture of parts have become a mainstream method for the development of advanced aircraft with high efficiency.

Taking aircraft tubular parts manufacturing as an example, FE simulation, three-dimensional CAPP, and technical database have been largely used in assisting technicians designing forming technology, such as designing tools, drafting fabrication orders and writing processing documents, which has greatly improved the accuracy and reliability in the design process of tubular parts. By using the FE analysis software, technicians can analyze the defect of bent tubular components, such as wrinkling, springback, thinning, and cracking, thus to predict bending quality, optimize process parameters, such as clamping force, bending speed and the extension length of mandrel [1-2]. However, the bent tubular parts always include several straight segments and bent segments. The bending process involves
repeated geometry movements of machine tools. The relative position of the tube is constantly changing during the forming process. Hence, only considering the forming quality can hardly meet the demands for digital, precise and intelligent manufacturing. The interactions between multiple curved segments, and between the tube and the machine tools are still significant problems.

Therefore, it is necessary to establish a geometry simulation system for complex bent tubular parts, and thus to clarify the repetitive motion relationships between the tube, tools, and bending machine. In this work, a geometry simulation model for continuous multi-bending is constructed and integrated with the tube forming FE simulation module. Based on the established geometry-FE coupled model, the simulation of continuously multi-bending process is conducted, and the forming quality of bent segment and interferences upon bending are realized.

2. Critical review for simulation of tube bending
Tube forming simulation is mainly divided into FE simulation and geometry motion simulation. The FE forming simulation mainly analyses the forming quality of a single bent segment from the physical aspect. The motion interference simulation mainly analyses the mutual influence and interference of each bending segments and the tools from macroscopic aspect.

The FE simulation originated from the “matrix algorithm” of structural mechanics in the United States in the 1940s. Then it was developed to be small deformation elastic-plastic FE theory in the 1960s [3] and large deformation elastic-plastic FE theory in the 1970s [4]. In the 1980s, the FE simulation was gradually applied in sheet metal forming, especially in the manufacturing processes of automobile parts [5]. In the 1990s, the FE simulation began to be professional and commercial, and some commercial FE software has emerged, such as Pam-Stamp, ABAQUS, MARC, ANSYS, and AutoForm, etc. After 2000, with the rapid development of computer technology, FE simulation began to be “day engineering” or even “2-hour engineering”. Simulation technology has been widely used in plastic forming fields, especially in the automotive industry. In recent years, some FE software has begun to introduce specific simulation analysis modules for specific forming processes, which simplifies pre-processing operations on the premise of ensuring accuracy and makes software closer to the actual application. For tube bending, “Pam-Tube 2G” is a typical case that based on the Pam-Stamp software, in which a special simulation analysis module is introduced for tube multi-bending. Pam-Tube 2G provides a more standard pre-processing for users and simplifies the modelling operations [6].

The geometry motion simulation originated from the automatic control in machine industry. Since the logical relationship of automatic control is quite different, the initial motion simulation is basically completed by a self-developed simulation program. After 2000, with the wide application of three-dimensional modelling software such as CATIA, UG, SolidWorks and ProE, motion simulation analysis was gradually integrated with modelling software. For example, the “DMU” module of CATIA can not only perform motion geometry simulation, but also can accurately calculate the interference amount [7].

FE simulation is widely used in aviation, aerospace, weapons, electronics, metallurgy and other industries in China. For tube bending simulation, Beijing University of Aeronautics and Astronautics and Shenyang Aircraft Company applied Pam-Tube 2G to conduct the bending simulation of aluminum alloy tubular parts [8-9]. Northwestern Polytechnical University used the Abaqus and Dynaform to predict the three-dimension bending deformation of difficult-to-deform materials and structures, such as high-strength thin-walled aluminum alloys, stainless steels, titanium alloys, etc. [10-12]. These studies mainly analyzed the forming quality and springback behaviors of a single bending segments of tubular part. However, the interference between the tube, the tools, and the machine, which may occur during continuous multi-bent tube forming, has not been considered. Shenyang Aeronautical University carried out geometry simulation of a multi-bending process [13] to analysis the interference of the bending process. However, the bending-induced unloading springback, flattening, are not considered, resulting in significant differences between simulation results and experimental ones.
3. Establishment of CATIA-based interference simulation system
Aiming at the demand of digital, precise and intelligent forming of complex tubular parts, this study establishes a knowledge base of tube bending simulation based on the knowledge engineering, and develops an interference simulation system for tube bending based on CATIA software. Figure 1 is an information flow of interference simulation system in tube bending. By extracting the tube model data and automatically selecting the machine model, die parameters, and forming parameters, a FE simulation model of a single bending segment is constructed, and Pam-Tube is called to obtain the forming rules of a single bending segment. On this basis, the geometry motion simulation model is sequentially constructed for different bending stages to calculate the interference amount, automatically generates the simulation analysis reports and the numerical control codes, and to realize the FE simulation and geometry motion simulation of continuous multi-bending process.

![Figure 1. Information flow of interference simulation system in tube bending](image)

3.1. Establishment of simulation knowledge base
The simulation knowledge base is one of the most significant issues in tube forming simulation system and determines the correctness and reliability of the simulation results. The simulation knowledge base is mainly composed of parameterized standard models, parameter data, and document templates. The standard models include a tube model, a machine model, a die model, a FE simulation model, and a geometry simulation model. The parameter data includes material parameters, forming process parameters, etc. The document templates include a simulation report template and a numerical control code rules. By collecting and standardizing the typical modelling process, material properties, forming processes, simulation reports, numerical control codes and other regulatory requirements and operation experience of technicians, simulation related information can be parametrically expressed to create a tube simulation knowledge base. The simulation knowledge base is not only a simple database, but also includes a decision-making mechanism, which clarifies the applicable conditions of each knowledge case. Considering that the simulation knowledge base involves a huge amount of information, inputting the information manually with software interfaces is quite low efficient. Thus, in the early stages, data records can be created through a spreadsheet, and finally integrated into the simulation knowledge base.
3.2. Extraction of model data
Based on the secondary development of CATIA, using the decision-making mechanism of the simulation knowledge base, the product figure number, material grades, material specification, space coordination and bending information are sequentially extracted from the product model parameters and geometry of bent tube, and the theoretical bending segment length and clamping margin length are calculated through the two-level decision-making of information path keywords and information content keywords. Then, the extracted information isstandardized to provide the necessary input conditions for subsequent simulation. The extraction process of tube model data is shown in Figure 2.

![Figure 2. Extraction of typical tube model data](image1)

3.3. Selection of process parameters
Based on the conditions of material grade, specification, bending radius and bending segment length, process parameters such as bending equipment, bending die and other technical parameters are automatically selected under the reasoning and driving of process knowledge. A complete set of tube die consists of 5 parts: bending die, clamping die, pressure die, wiper die and mandrel shank and mandrel ball. Besides, the coordination and cooperation of each tool are also the key part in this decision-making process. The automatic selection of typical tooling parameters is shown in Figure 3.

![Figure 3. Automatic selection of tool parameters](image2)

3.4. FE simulation of single bending
Using Pam-Stamp FE software, the data exchange interface is developed. Taking the single bending segment of a continuous multi-bending process as the typical case, parameter-driven standard tube model, die model and FE simulation model can be constructed by calling the Pam-Tube simulation module. Then, the forming characteristics of the single bending segment can be obtained. The FE simulation of the single bending segment of the tubular part is shown in Figure 4.

![Figure 4. FE simulation of single-bending](image3)

3.5. Geometry simulation of multi-bending
According to the results of the FE simulation of single bending, the forming quality rules can be analyzed, and the parameterized expressions can be carried out to obtain the bending information such as the springback angle and elongation. Via the secondary development of CATIA, a parameter-driven geometry motion simulation model of tube multi-bending is established. Then, by calling the “DMU”
module, the interference amount between the tube, dies and machine tool can be calculated. Through “Modify Parameter → Model Reconstructing → Calculating Interference Amount” cycle, the single step geometry motion simulation of the tube is realized. Through the “Clamp Die Rising → Clamp Die Clamping → Pressure Die Pressing → Bending → Springback → Clamping Die Retreating → Clamping Die Lowering → Pressure Die Releasing → Car Feeding → Bending Die Resetting” multi-step cycle, the geometry motion simulation of continuous multi-bending can thus be achieved. The geometry simulation of typically complex multi-bending process is shown in Figure 5.

3.6. Generation of simulation report
According to the simulation results, the result parameters and picture information are imported into the simulation report template. The simulation reports of a typical complex tube forming are shown in Table 1. According to the definition format of the motion track of bending machine, the simulation result is used as the input condition to automatically establish the numerical control code. The design process of numerical control code is mainly realized by software.

| No. | Step name             | Figure | Result                                           |
|-----|-----------------------|--------|--------------------------------------------------|
| 001 | System Initialization | ![Image](image1.png) | No interference                                  |
| 009 | Bending               | ![Image](image2.png) | No interference                                  |
| 015 | Bending Die Resetting | ![Image](image3.png) | Interference amount between tube and bending die is 34.333mm |
|     |                       |        | Interference amount between tube and bending die is 31.215mm |
|     |                       |        | Interference amount between tube and clamping die is 23.773mm |
| 018 | Clamping              | ![Image](image4.png) | Interference amount between tube and clamping die is 63.244mm |
|     |                       |        | Interference amount between tube and clamping die is 23.918mm |
| 022 | Bending               | ![Image](image5.png) | No interference                                  |
| 029 | End                   | ![Image](image6.png) | No interference                                  |

3.7. Batch processing
Considering the large amount of simulation work in the aircraft development stage, it is important to achieve batch automatic simulation to improve the development efficiency. Through repeated cycles of opening model, extracting of model data, selecting of process parameters, FE simulation of single bending, geometry simulation of multi-bending, and generating simulation result file, batch processing can thus be achieved. To prevent special situations, such as errors in opening model and simulation, the system regularly detects the simulation progress information. The processing will be forced to termination and transform to the next simulation step, when the current data processing does not yet complete at the predetermined time.

4. Typical applications
Through the construction of simulation knowledge base and software development, a CATIA-based tube bending interference simulation system is established. At present, the tube bending interference simulation system has been successfully applied in the development of a civil aircraft. By using the
system, batch of forming simulations have been achieved, and simulation analysis reports and numerical control codes have been automatically generated. The forming quality and tube bending interference of the single bending segment have been obtained. Besides, the application the established system can effectively improve the developing efficiency of aircraft tubular parts, and significantly reduce the labor intensity of technicians.

5. Conclusions

The CATIA-based tube bending interference simulation system fully combines the advantages of FE simulation and geometry motion simulation. Using the system, the three-dimensional model of tube bending is established, the continuous multi-bending simulation analysis is realized, the quality and interference situation of the tube forming are obtained, and the developing efficiency of bent tubular parts is greatly improved, and the labor intensity is significantly reduced.

References

[1] Yang H, Li H, Zhang Z Y, Zhan M, Liu J and Li G J 2012 Advances and trends on tube bending forming technologies Chinese Journal of Aeronautics vol 25 pp 1-12
[2] Li H, Yang H, Zhan M, Sun Z C and Gu R J 2007 Role of mandrel in NC precision bending process of thin-walled tube International Journal of Machine Tools and Manufacture vol 47 pp 1164-1175
[3] Yamada Y, Yoshimura N and Sakurai T 1968 Plastic stress-strain matrix and its application for the solution of elastic-plastic problems by the FE method International Journal of Mechanical Sciences vol 10 pp 343-354
[4] Oden J T, Bhandari D R, Yagawa G and Chung T J 1973 A new approach to the FE formulation and solution of a class of problems in coupled thermo elastovisco plasticity of crystalline solids Nuclear Engineering and Design vol 23 pp 420-429
[5] Hamel V, Roelandt J M, Gacel J N and Schmit F 1988 Finite element modeling of the punch stretching of square plates Journal and application of Mechanical vol 55 pp 667-671
[6] Zou X W 2006 ESI group launched a professional solution for virtual manufacturing curve and hydraulic simulation prediction simulation - PAM-TUBE 2G software Forging & Metal forming pp 18-18
[7] Liu S T, Chen X M, Zhao Z D and Yin H B 2015 Research on motion simulation of aircraft landing gear Aeronautical Manufacturing Technology vol 475 pp 89-91
[8] Zhang D X, Yu X C, Zhou S, Du P M and Xue X F 2011 Simulation analysis on forming laws of NC tube bending based on PAM-TUBE 2G Forging & Stamping Technology vol 36 pp 148-151
[9] Tao Y M, Liu F, Sun J N, Wang S H and Wang W 2007 Numerical simulation analysis of tube bending process using PAM-TUBE 2G Aeronautical Manufacturing Technology vol s1 pp 300-302
[10] Yan J, Yang H, Zhan M and Li H 2010 Forming limits under multi-index constraints in NC bending of aluminium alloy thin-walled tubes with large diameters Sci China Tech Sci pp 326–342
[11] Wang Z K, He Y, Li H, Ren N, Lu R D and Tian Y L 2012 Springback laws of large diameter 316L stainless steel tube in NC bending Materials Science & Technology vol 20 pp 49-54
[12] Song F F, Yang H, Li H, Zhan M, Wang Y and Li G J 2013 Significance Analysis of Processing Parameters Effect on Springback in High Strength TA18 Tube NC Bending Rare Metal Materials & Engineering vol 42 pp 43-48
[13] Han Z R, Liang W X, Liu B M and Li G J 2015 Research on the simulation technology for NC tube bending process based on CATIA Manufacturing Automation pp 38-40