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APPLICATIONS WITH A NEW 6-DOF BENDING MACHINE IN TUBE FORMING PROCESSES

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ABSTRACT

This research presents a new flexible bending machine and its practical applications. The proposed machine uses a new method. When tubes are fed into the fixed and mobile dies, they are bent by shifting the relative position of the mobile die. The bending radius is controlled by the relative distance and orientation between the mobile die and the tube. The bending angle is controlled by the length of the fed tube. This forming process has a big advantage. A change of the expected bending shape will need no change in the tooling system but only a new definition of the motion of the active die and the length of the fed tube. The active die movements are controlled by a 6-DOF parallel kinematics mechanism (PKM) with hydraulic servo drive. Making use of the PKM serves not only to achieve a complete motion along six axes but also to obtain a high dynamic motion of the bending machine. Application examples show that the bending machine can be applied to designer's interiors, universal designed products, and automotive parts. Until now these processes have been difficult to achieve using a conventional bending machine.

KEY WORDS

Parallel kinematics mechanism, Hexapod, Hydraulic servo, Tube forming, Free-form bending,

NOMENCLATURE

R	:	Bend radius.
u	:	Offset .. .
L	:	Distance between dies...
F	:	Working load.
F_p	:	Pushing load.
α,β,γ	:	Euler angle of a moving die.
P	:	Point located at the canter of a moving platform.
O	:	Origin of the fixed platform.
A_i	:	i th ball point on the fixed base.
B_i	:	i th ball point on the moving platform.
$\mathbf{P}$	:	Position vector of a point P with respect to origin of the fixed platform.
$\mathbf{a}_i,\mathbf{b}_i$	:	the position vectors of points A_i and B_i.
${}^{A}R_{B}$	:	Rotation matrix that describes the orientation of frame B with respect to frame A.
$\mathbf{u},\mathbf{v},\mathbf{w}$	:	Unit vector pointing along the u,v,w-axis of a moving frame.

INTRODUCTION

Bent tube products are employed in manufacturing many kinds of products such as fluid arrangements, furniture, transport apparatus, and mechanical parts, as required for reduction of production cost and weight.

For basic bending methods of tubes, (1) rotary-draw bending, (2) press bending, and (3) roll bending, have been commonly used. The rotary-draw bending is the most standard method used on rotary-type bending machines, which can be powered, manual, or numerically controlled. The draw bending consists of the rotating bending form, clamping die, and pressure die. The workpiece is secured to the bending form by a clamping die. As the bending die rotates, it draws the workpiece against the pressure die. These machines handle about 95% of tube bending operations [1]. The press bending method uses simple tooling and is quick and easy to set up. The major advantage of press bending is its high production capabilities but it has less accuracy. Roll benders use the basic principal of force applied between three rotating rolls. The material enters the rolls and roll pressure causes it to yield on the underside of the center roll.

Besides these conventional techniques, a new flexible CNC bending machine which is based on the MOS bending method [2] has been developed. MOS bending is a versatile and flexible method for a free-form circular tube. However, this method can not bend a square or rectangular tube. For the hydroforming of space frame components, there are the increasing needs for three-dimensional free-form bending profiles of non-circular tubes.

This paper, therefore, presents a new flexible bending machine for non-circular tubes and profiles that are difficult to bend using conventional bending machines.

BASIC CONCEPT

The applied basic concept [3] is shown in Figure 1. Two tooling dies are used for the bending process. One is fixed and the other one is actively moved forming the part to be bent. Both dies are shaped in accordance with the outside shape and parameters of the tube or profile. The tube or profile is pushed through the fixed die and is bent by the motion of the mobile die. Pusher movement and movement of the mobile die are synchronized. When the tubes are fed into the fixed and mobile die, they are bent by shifting the relative position of the tube. The bending radius *R* is controlled by the relative distance between the die and the tube. The bending angle is controlled by the length of fed tube.

This forming process has a big advantage. A change of the expected bending shape will need no change in the tooling system but only a new definition of the motion of the active die and synchronization of the pusher.

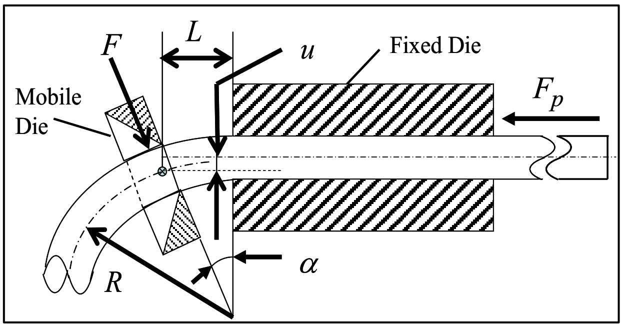

Figure 1 Basic concept

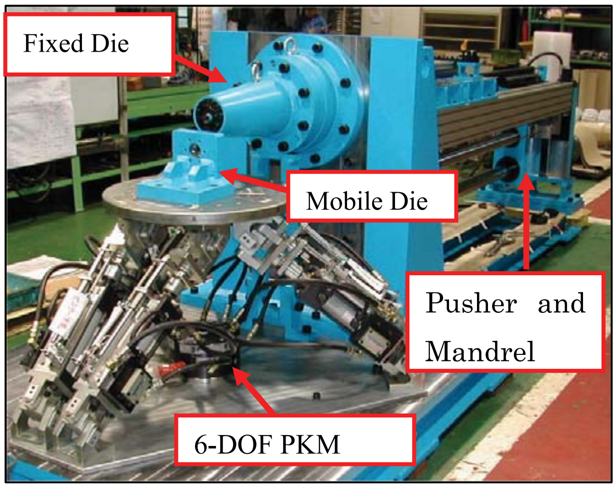

Figure 2 The proposed bending machine

MACHINE STRUCTURE AND DESIGN

Figure 2 shows the schematic of the proposed bending machine. This machine consists of a mobile die with a 6-DOF parallel kinematics mechanism, a fixed die, a pusher and a mandrel.

Mobile Die and 6-DOF PKM

The active die movements are controlled by a 6-DOF parallel kinematics mechanism (PKM). Making use of the PKM serves not only to achieve a complete motion along six axes but also to obtain a high dynamical motion of the bending machine.

Fixed Die

The mounting carries the rigid fixed die and must absorb the press force in conjunction with the frame components.

Pusher

The feeding or pusher module creates a controlled feeding motion of the workpiece in the bending zone to generate the bending geometry. The feeding motion is defined as a function of the corresponding forming procedure. The pusher is driven by a hydraulic servo motor. The rotary motion is transformed into a translation one upon a ball screw. Within this module, feed forces up to 40kN and positioning accuracy of ±0.1mm can be achieved in this machine. In the prototype bending machine, profiles up to a length of 2300mm can be formed. In order to avoid buckling risk, the profile runs through a conduit which completely encapsulates it. This conduit depends upon the profile's cross-section and must be changed for another profile cross-section. The conduit is split into a right and left box in conjunction with an automatic profile feeding module. The conduit can be opened manually.

Mandrel

The mandrel is a tool inserted in a tube or pipe in the region of the bend tangent. This tool is not only to diminish the risk of buckling, but also to reduce wall thickness alterations, distortion and torsion of the cross-section. On the proposed machine, the mandrel is attached to a rod anchored at the rear of the machine. The rod incorporates lateral and longitudinal adjustment capability to position the mandrel in relation to the bend radius and at the point of the bend.

KINEMATIC MODELING

Figure 3 and 4 show this 6-DOF PKM known as a Stewart-Gough platform [4]. Six identical limbs connect the moving platform to the fixed based by spherical joints B_i and A_i, $i=1,2,...,6$, respectively. Each limb consists of an upper member and lower member connected by a prismatic joint. Ball screws can be used to vary the lengths of the prismatic joints and therefore to control the location of the moving platform. For the purpose of analysis, two Cartesian coordinate systems, frames $A(x,y,z)$ and $B(u,v,w)$ as shown in Fig.4, are attached to the fixed based and moving platform, respectively. The transformation from the moving platform to the fixed base can be described by the position vector $\mathbf{p}$ of the centered P and the rotation matrix ${}^{A}R_{B}$ of the moving platform. Let $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{w}$ be three unit vectors defined along the u , v and w axes of the moving coordinate system; then the rotation matrix can be written as:

$$ {}^{A}R_{B} = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} \tag{1}$$

As shown Fig.4, let $\mathbf{a}_i = \left[a_{ix}, a_{iy}, a_{iz}\right]^{\mathrm{T}}$ and $\mathbf{b}_i = \left[b_{iu}, b_{iv}, b_{iw}\right]^{\mathrm{T}}$ be the position vectors of points A_i and B_i, respectively. We can write a vector-loop equation for the th limb of the manipulator as follows:

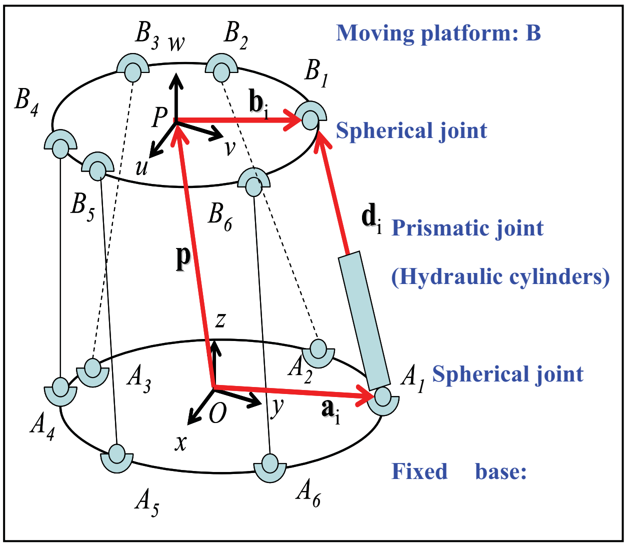

Figure 3 Kinematic modeling (Stewart-Gough platform)

$$\overline{A_iB_i} = \mathbf{p} + {}^{A}R_{B}\mathbf{b}_i - \mathbf{a}_i \tag{2}$$

The length of the i th limb is obtained by taking the dot product of the vector with itself:

$$\begin{aligned} d_i^2 &= \mathbf{p}^{\mathrm{T}}\mathbf{p} + [\mathbf{b}_i]^{\mathrm{T}}[\mathbf{b}_i] + \mathbf{a}_i^{\mathrm{T}}\mathbf{a}_i \\ &+2\mathbf{p}^{\mathrm{T}}\left[{}^{A}R_{B}\mathbf{b}_i\right] - 2\mathbf{p}^{\mathrm{T}}\mathbf{a}_i - 2\left[{}^{A}R_{B}\mathbf{b}_i\right]^{\mathrm{T}} - \mathbf{a}_i \end{aligned} \tag{3}$$

where d_i denotes the length of the i th limb. Taking the square root of Eq. (3) we obtain:

$$\begin{aligned} d_i = \pm\Big[&\mathbf{p}^{\mathrm{T}}\mathbf{p} + [\mathbf{b}_i]^{\mathrm{T}}[\mathbf{b}_i] + \mathbf{a}_i^{\mathrm{T}}\mathbf{a}_i \\ &+2\mathbf{p}^{\mathrm{T}}\left[{}^{A}R_{B}\mathbf{b}_i\right] - 2\mathbf{p}^{\mathrm{T}}\mathbf{a}_i - 2\left[{}^{A}R_{B}\mathbf{b}_i\right]^{\mathrm{T}} - \mathbf{a}_i\Big]^{1/2} \end{aligned} \tag{4}$$

for $i=1,2,...,6$. Hence, corresponding to each given location of the moving platform, there are generally two possible solutions for each limb. However, a negative limb length is physically not feasible. When the solution of becomes a complex number, the location of the moving platform is not reachable.

CONTROL SYSTEM

PKM with six degrees of freedom using six electro hydraulic servo cylinders has large rigidity and support power. This feature is widely used for a driving device with multi degrees of freedom that has a heavy load and needs a large driving force. These hydraulic PKM focusing on major acceleration forces are flight simulators, which requires a high degree of dynamics in

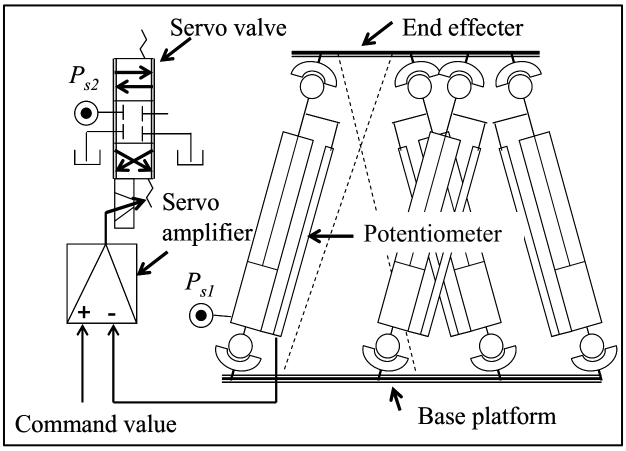

Figure 4 Hydraulic control system

their guidance behavior. On the other hand, for hydraulic PKM in the bending machine, the focus is on high positioning accuracy and load rigidity. Figure 4 shows the electro hydraulic servo control system for the proposed bending machine.

EXPERIMENTS

Basic Bending

In order to evaluate the performance of the proposed bending machine, basic bending was performed. Figure 5 ,6 and 7 show an overview of the basic bending.

The bending radius *R* of the tube is decided by the magnitude of offset *u*. The relationship between the offsets *u* and the bending curvature *1/R* is shown in Figure 8 as a parameter of material shapes. The relationships can be obtained by bending experiments. The flexural rigidity, Young's modulus and other material properties vary with changes of materials and dimensions of the tubes. Therefore, the bending radius *R* fluctuates even though the offset *u* does not change. But this bending machine can bend the tubular workpiece into a certain bending radius by adopting a suitable relationship of *u* and *R* for the tube, even though the tubular material or dimensions change.

APPLICATIONS

Experimental results show that the bending machine can be applied to many kinds of products such as furniture, universal designed products, and automotive parts. Until now these manufacturing processes have been difficult to achieve using a conventional bending machine.

The designer interior

The new bending machine has no limit for the designers' request about shapes as compared with the conventional bending machine. Therefore, designers can display their ability to create a new design concept.

Figure 5 Results of the square tube bending (aluminum)

Figure 6 Results of the circular tube bending (aluminum)

Figure 7 Result of the circular tube bending (steel)

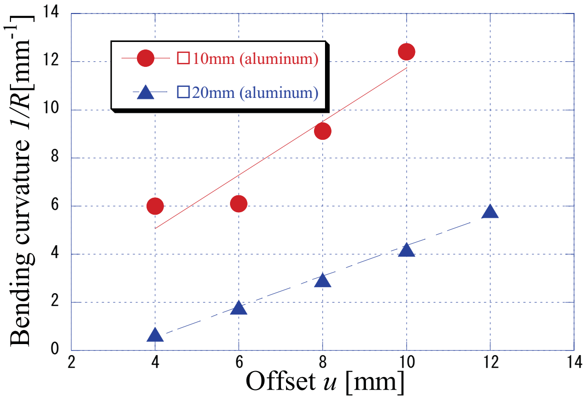

Figure 8 Relationships between *u* and *1/R*

Figure 9 The sketch of "STROKE vase"

Figure 10 the vase production

Figure 9,10 and 11 shows the designers' image sketch and the vase product as an example.

Universal Design

The human body has very complex and three dimensional shapes. Therefore, the medical equipment's parts such as a handrail should be made to fit for the complex and three dimensional human body shapes. When the handrail is made by a conventional bending machine, the bending process is very difficult and many days are needed for preparing the dies. But, if the new bending machine is used, the complex shaped handrail can be easily produced after a little trial bending.

Extrusion bending

Bent thin-walled aluminum extrusions (see Figure 14) have great potential for automotive parts. However, extrusion bending process has been difficult to achieve using a conventional bending machine. Figure 15 and 16 show the results of extrusion bending. Experimental results show that the bending machine can be applied to extrusion bending process.

Figure 11 "STROKE vase"

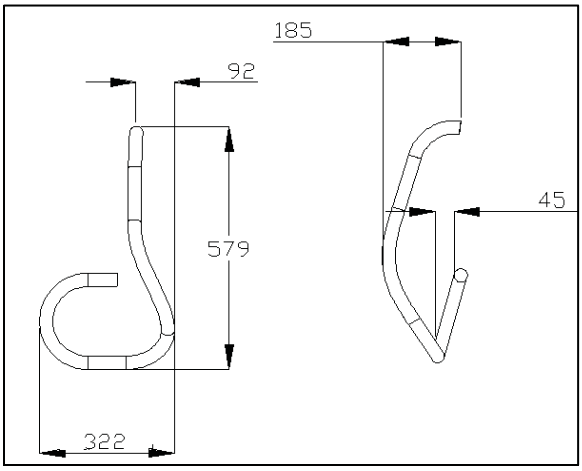

Figure 12 The design of a handrail

Figure 13 The handrail with universal design

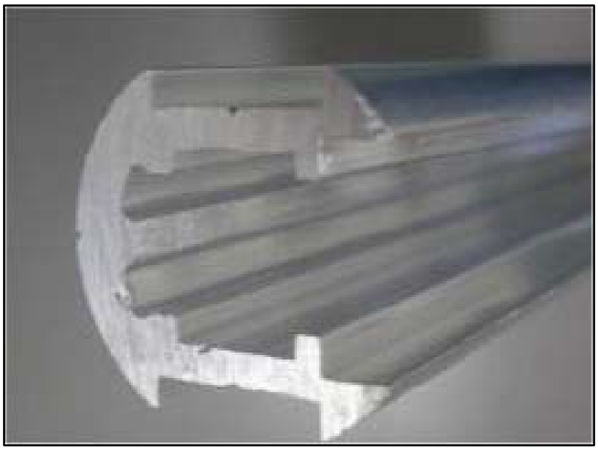

Figure 14 An aluminum extrusion

Figure 15 An example of the extrusion bending

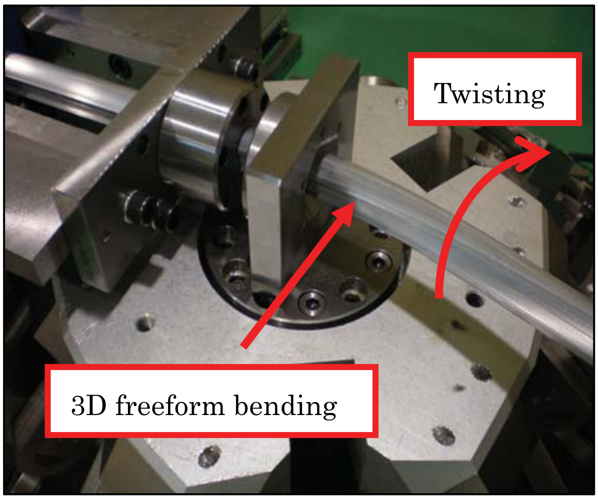

Figure 16 An example of the extrusion bending process

CONCLUSION

In this paper, a new flexible bending machine for tubes and profiles that are difficult to bend using a conventional bending machine was proposed. This system utilized the 6-DOF PKM as a controlling mobile die. The geometrical relationship between the moving platform and the length of six limbs of the PKM were formulated. The electro hydraulic servo control system for the bending machine was also proposed. The hydraulic PKM has been focusing on high positioning accuracy and load rigidity. Experimental results show that the bending machine can be applied to designer's interiors, universal designed products, and automotive parts. Until now this process has been difficult to achieve using a conventional bending machine.

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