STOCHASTIC MODELING AND ADAPTIVE CONTROL ALGORITHM OF BRAKE BENDING*

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Abstract

Among the many industrially important processes of forming, brake bending occupies a dominant position in aricraft production. The basic feature of brake bending is that the geometric nonlinearity due to large deflection incorporated with tool geometry arieses associated with material nonlinear behavior. Furthermore, the mechanical behavior is extremely sensitive to the method and parameters of processing used in the upstream stages of sheet metal production and may exhibit significant diference which is propabilistic in nature. The basic purpose of this study is to propose a stochastic model of brake bending, in which the variation of material characteristics is considered to be the most important disturbance in the process, and to develop an adaptive control algorithm capable of handling such variation automatically, thus reducing the amount of scrap and machine downtime and increasing productivity. To verify the stochastic model and the adaptive control algorithm proposed, a series of brake bending tests have been performed and good results have been attained.

1. Introduction

Brake bending is utilized heavily in the production of aircraft. However, in a typical aircraft company more than 90 percent of brake-bent parts are formed by air or free bending operation [1], in which the penetration of the V-punch into the U-die governs the bend angle. The determination of the proper punch travel to yield the desired final angle after springback is frequently done manually using a trial-and-error method, and hence is cumbersome and time-consuming, especially in the case of small-batch production.

The need of forming high quality parts with high flexibility of operation is becoming more and more apparent in aerospace industry. The results obtained in terms of savings and added productivity have been most encouraging by adopting NC pressbrakes, in which the control input is the punch travel and the output is the final bending angle. However, the final angle is influenced by some seemingly elusive variations of work variables, among these are intrinsic and extrinsic properties of the sheet material. To effect part control for a pressbrake, some adaptive controllers have been designed.

Gossard and Allison [2] have developed an iterative system, in which a flank angle sensor is built in the die. At a loading signal, the punch travels until the measured angle reaches the command value. After complete unloading, the difference between command and measured angles is added to the desired value to give a new command angle and to issue a new

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loading signal. Having implemented multiple loadings, the desired final angle with remarkable accuracy can be achieved. This algorithm needs no material information and might be regarded as a mechanized trial-and-error procedure in essence.

Stelson and Gossard [3] have presented another adaptive controller, which measures force and displacement of the punch during loading to estimate workpiece parameters. Thses parameters are then used in an elastic-perfectly plastic material model to predict the correct final punch position to yield the desired unloaded angle. Afterwards, the adaptive control algorithm proposed in [3] has been generalized by Stelson [4], and the material model has been improved to be elastic, strain-hardening and elastic, power-law strain-hardening [5] so that the tendency of overbend due to elastic-perfectly plastic material model can be eliminated. For improving thses algorithms, Kim and Stelson [6] have proposed a calibration procedure using a finite element analysis of brake bending. Since the simplified elastic-perfectly plastic and elastic, power-law strain-hardening materials are still used in the finite element analysis, the accuracy of the calibrated algorithm remains to be improved.

In previous papers by the author [7,8], a deterministic model of brake bending has been proposed, in which behavior of the sheet is completely described by its real curvature-moment relationship obtained from experiments. In this study the variation of mechanical behavior for a specific material is defined from a specially designed bending test and is introduced to the deterministic model by Monte Carlo simulation. This leads to a stochastic modeling and a novel adaptive control algorithm of brake bending.

2. Deterministic Model

It is assumed that the sheet is deformed by bending along in brakeforming process, and shear deformation and axial force effect are neglected. The mechanical behavior of the sheet is hence completely described by its curvature-moment relationship, which can be defined by spline fitting to a set of experimental data and can be written as

$$K=\sum_i c_i (M-M_i)_+^m \qquad (1)$$

where c_i' s are constants and M_i' s stand for breakpoints of M. The truncated power function in the form of $(M-M_i)_+^m$ in Eqn. (1) is defined as

$$(M-M_i)_+^m=\underbrace{\int\cdots\int}_{m+1}\delta(M-M_i)\underbrace{dM\cdots dM}_{m+1}$$

in which $\delta(M\text{-}M_i)$ is Dirac delta function.

The sheet to be bent is discretized into a number of 2-node segments. For a generic segment, the jth one, the secant line passing through the nodes s_{j-1} and s_j, where s is curve length of the neutral surface from a starting point, is referred to as the local axis x_j. The configuration of jth segment can be defined in terms of $y_j=y_j(x_j)$ in the local Cartesian coordinate system with the origin at s_{j-1}. By taking a sufficiently large number of segments with sufficiently small lengths, all the slopes of the sheet with respect to the local exes x_j' s can be made as small as desired. Therefore, in each segment, the linear theory

$$K(s)=y_j''(x_j),$$

$$s\in[s_{j-1},s_j],\ x_j\in[0,l_j] \qquad (2)$$

and the approximate relations

$$ds=dx_j,\ l_j=s_j-s_{j-1}$$

are applied.

In this segment, the moment can be written in terms of Taylor' s expansion

$$M(x_j)=\sum_{k=0}^{n} M_{j-1}^{(k)} x_j^k/k!$$

In the case of brake bending, it is desired to take n=1, i.e.

$$M(x_j)=M_{j-1}+V_{j-1}x_j \qquad (3)$$

where M_{j-1} and V_{j-1} are bending moment and shear force at s_{j-1}, respectively (Fig. 1).

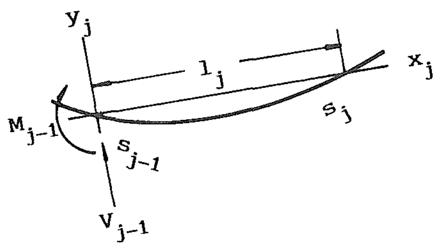

Fig. 1 Bending moment and shear force at s_{j-1}

Denoting the upper and lower bound of the moment distribution of the jth segment as L_j and U_j respectively, we have

$$L_j \leqslant M(x_j) \leqslant U_j, \qquad x \in [0, l_j]$$

Within the sufficiently small interval $[L_j, U_j]$, the first approximation of Eqn. (1) can be adopted, i. e.

$$K = a_j + b_j M \qquad (4)$$

where

$$a_j = (K_L U_j - K_u L_j)/(U_j - L_j)$$

$$b_j = (K_U - K_L)/(U_j - L_j)$$

and (K_L, L_j), (K_U, U_j) both satisfy Eqn. (1).

Combining Eqns. (2), (3) and (4), we have

$$y''_j(x_j) = a_j + b_j(M_{j-1} + V_{j-1}x_j) \qquad (5)$$

Intergration of Eqn. (5) subjected to boundary conditions, $y_j(0) = y_j(l_j) = 0$, yields

$$y'_j(x_j) = (a_j + b_j M_{j-1})(2x_j - l_j)/2 + b_j V_{j-1}(2x_j - l_j^2)/6$$

$$y_j(x_j) = (a_j + b_j M_{j-1})(x_j - l_j)x_j/2 + b_j V_{j-1}(x_j^2 - l_j^2)x_j/6$$

The tangent continuity of the sheet at point s_j gives the rotation φ_j from x_j to x_{j+1} (Fig. 2), and

$$\varphi_j = y'_j(l_j) - y'_{j+1}(0)$$

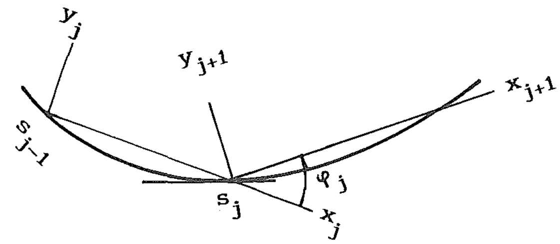

Fig. 2 slope continuity of the sheet at s_j

When the φ_j' s have been found, and the coordinates and tangent of the sheet at the starting point have been specified in a global Cartesian system, the entire configuration of the sheet under loading is uniquely defined. In a similiar manner, the configuration of the sheet after unloading can also be obtained.

3. Curvature-Moment Relationship

To obtain the curvature-moment experimental data, bending tests have been carried out on the apparatus schematically shown in Fig. 3. The test can

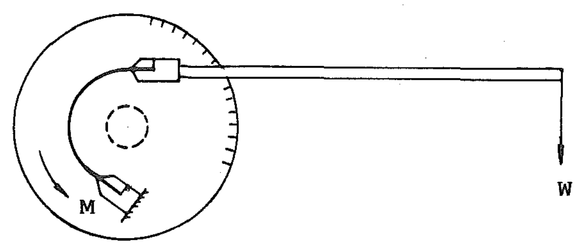

Fig. 3 Bending apparatus

be recognized approximately as a pure bending test with an appropriately long arm, of which the length depends on the allowed deviation of the moment distribution of the specimen from that of pure bending. The bending moment applied to the specimen is measured by the weight W while the curvatures of loading and unloading by the dial on turntable and followed by a sequence of calculations.

The specimen is 60mm long, 25mm wide, and is cut from aluminium alloy LY12M sheet of 1.5mm thick. At the middle of the specimen is the bending area, which has a length of 15mm. Having gripped the specimen by a fixed and a freely movable chuck and applying a concentrated load of 100 grams to the arm at a fixed distance from the center of the bending area, the curvature under loading can be specified, then the specimen is unloaded and the curvature after springback can be obtained either. This procedure is repeated until all the loads of 200, 300, 400, 450, 480, 510, 540, 570 and 600 grams are seperately applied to the arm in order of magnitude.

The histograms of 150 measurements of curvature after each loading and unloading in the bending test suggest that the related distribution functions tend to be Gaussian. The generalized chi-square test shows that all the χ^2-values of the curvature samples of loading and unloading are less than $\chi^2_{0.01}(7)$, and thus the hypothesis that the distributions of the curvature populations of loading and unloading are normal can be accepted.

Using least-square method, means of K_i, i. e. $\bar{K}_i$ $(i=1,2)$, where K_1 and K_2 are curvatures of loading and unloading respectively, can be defined in the form of Eqn. (1) with relevant constants and breakpoints. The standard deviations of K_i, e. i. σ_i $(i = 1, 2)$, can also be fitted by least-square method as monotonically increasing functions of moment

$$\sigma_i = D_i(M), \qquad i=1,2$$

Since only restricted ranges of the random variables $K_i(i=1,2)$ are concerned, the truncated normal distribution functions are adopted, and the distribution surfaces of K_i versus M can be expressed as follows

$$F_i(K_i,M) = \begin{cases} \dfrac{1}{\sqrt{2\pi}D_i f_i} e^{\frac{-(k_i-\bar{k}_i)^2}{2D_i}}, & \text{for } K_i \in T_i \\ 0, & \text{otherwise} \end{cases}$$

$$i=1,2$$

where

$$f_i = \int_{T_i} \frac{1}{\sqrt{2\pi}D_i} e^{\frac{-(k_i-\bar{k}_i)^2}{2D_i}} dK_i$$

$$T_i = [\bar{k}_i - 3D_i, \bar{k}_i + 3D_i]$$

$$i=1,2$$

The upper and lower bound of the distribution of K_i versus M, i. e. K^+ and K^-, respectively,

$$K_i^+ = \bar{K}_i + 3D_i$$

$$K_i^- = \bar{K}_i - 3D_i$$

also can be defined in the form of Eqn. (1) with relevant constants and the same breakpoints as that of $\bar{K}_i$.

4. Stochastic Modeling

The basic problem in stochastic modeling of brake bending is the determination of the random nature of some dependent variables of interest, such as flank angles of loading (α_i) and unloading (α_2), which are known functions of some variables having knowm random natures. Among those random variables, only the bending characteristics, or namely the curvature-moment relationship, is concerned in this study. To solve this problem, the Monte Carlo method is adopted.

The monte Carlo method pretends that each trial is an actural measurement of the bending characteristics of one sheet to be bent, and each imaginary sheet varies its K-M relationship randomly from all others in accordance with the distribution surfaces of $K_i(i=1,2)$ versus M.

For generating a theoretical sample, the multiplicative congruential method is used, and a pseudo-random sequence uniformly distributed can be obtained by the recurrence relation

$$x_i = \lambda x_{i-1} (\text{mod } L) \qquad (6)$$

where λ, L are integers and λ is to be selected to have certain desired value related to L.

Using a sequence of uniformly distributed radom numbers generated by Eqn. (6) and a set of arbitrarily selected points on the normal curve as input, a sequence of numbers that are randomly and normally distributed over T_i can be obtained by a series of linear equations which approximates the normal curve

$$f_a(x)=c\left[f_{i-1}+\frac{x-x_{i-1}}{x_i-x_{i-1}}(f_i-f_{i-1})\right],$$

$$x_{i-1}\leqslant x\leqslant x_i$$

where c is normalizing factor, and x_i' s are selected points on the normal curve, f_i' s are related values of normal distribution function at selected points. The sampling numbers which are randomly and normally distributed are given by

$$S_j=x_{i-1}+\frac{r_j-f_a(x_{i-1})}{f_a(x_i)-f_a(x_{i-1})}(x_i-x_{i-1}),$$

$$f_a(x_{i-1})<r_j\leqslant f_a(x_i)$$

where r_j' s are a sequence of numbers which are randomly and uniformly distributed.

Based on the theoretical sample of 400 experiments by the Monte Carlo simulation under given working conditions of brake bending, the chi-square tests show that the hypothesis that the distributions of α_1 and α_2 are to be normal can be accepted. Then, means and standard deviations of α_i, i. e. $\bar{\alpha}_i$ and d_i $(i=1,2)$, as functions of H are defined by least-square method and spline fitting.

5. Adaptive Control Algorithm

Once a specific curvature-moment relationship as an event occurs, the relevant sheet will deform according to this relationship both in the cases of loading and unloading. Along with the punch descending, the flank angle under loading of the sheet that posesses the specific bending characteristics varies its value as a specific curve in α_1 vs H diagram (Fig. 4) within the interval of $[\bar{\alpha}_1-3d_1, \bar{\alpha}_1+3d_1]$. The final flank angle of this sheet for different punch travels also forms a specific curve in α_2 vs H diagram (Fig. 5) within the interval of $[\bar{\alpha}_2-3d_2, \bar{\alpha}_2+3d_2]$.

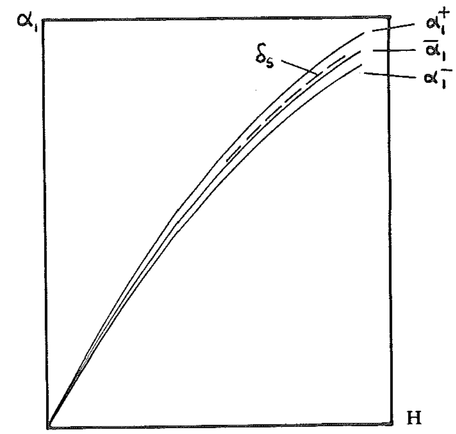

Fig. 4 Distribution range and meam of α_1 vs H

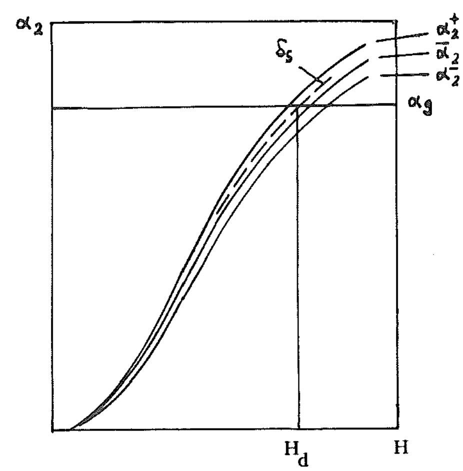

Fig. 5 Distribution range and mean of α_2 vs H

For indicating the deviations of specific curves of α_i $(i=1,2)$ versus H from their mean values, the drifting parameters δ_i are defined such that

$$\delta_i=\frac{\alpha_i-\bar{\alpha}_i}{3d_i},\quad i=1,2$$

As an approximation, it is assumed that δ_1 and δ_2 of the sheet that pocesses specific bending characteristics are identical, i. e.

$$\delta_1=\delta_2=\delta$$

and obviously

$$-1\leqslant\delta\leqslant1$$

On the basis of real time measured flank angle-punch displacemant data in the early stage of bending process, the drifting parameter δ can readily be estimted by a least-square method. This procedure is essentially an implicit form of in-process identification of workpiece material characteristics.

Using this drifting parameter identified, denoted by δ_s, the desired punch travel H_d can be readily predicted from the population of α_2 vs H for a given final flank angle α_g (Fig. 5).

To verify the stochastic simulation and the adaptive control algorithm proposed, a series of tests have been performed in laboratory environment using a numerically controlled material test machine equipped with linear and angular displacement sensors. Specimens are 200 mm long, 30mm wide, and made of the same material as that used in the bending characteristics test. The radii of punch and die are 15mm. The errors in final flank angles from 10 deg up to 40 deg fall within the interval of $\pm$50min, and exhibit a central tendency. No overband, which was reported in [5], has been observed in tests.

6. Conclusions

The adaptive control algorithm proposed in this paper features its two-phase structure. Phase one consists of precisely defining the curvature-moment relationship and stochastic modeling of brake bending process. Although phase one is a heavily loaded stage, all its work is performed out of the bending process. Phase two includes identification of workpiece material characteristics and prediction of desired punch travel. Operations on phase two are performed in-process, but are rather simple, especially compared with those methods reported in the literature [3-6].

The stochastic model of brake bending presented in this paper eliminates any simplified material model, and a higher accuracy of its results compared to those methods reported in [3-6] can be expected.

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