Motion Curve Optimization Algorithm Using Genetic Operations and Its Application to Bottling Machine

Ken'ichi Kanazawa[1], Ken'ichi Yano[1] and Tatsuhiro Nakada[2]

Abstract— We propose a motion curve optimization algorithm based on a genetic algorithm. A motion curve is a function of displacement of a drive part of a machine with respect to time. In a curve optimization using a standard genetic algorithm, an optimized curve is searched by repeatedly applying genetic operations to design variables that define the shape of motion curves. In contrast, the algorithm we proposed can effectively optimize a curve by directly applying genetic operations to curves without design variables. Eventually, the algorithm is applied to an optimization of a motion curve to decrease vibration at the surface of the liquid in a bottle using an actual bottling machine.

I. INTRODUCTION

High-speed bottle conveyances have recently become a requirement for bottling machines. The movement of the drive part of these industrial automatic machines is generally predefined as a motion curve (or cam curve). A motion curve is a function of displacement of an object with respect to time [1], [2]. Toward that end, optimum motion curves for suppressing vibration at the surface of liquids are required for conveying bottles at high speed without spilling the liquid.

Many studies have been carried out on vibration suppression control for surfaces of liquids [3], [4]. Yoshida et al. proposed a transfer control method for a cylindrical container for liquids by regarding it as a spherical pendulum-type sloshing model [5]. However, since the shape of most actual bottles is not as simple as a cylindrical container for liquid, applying that method to an actual bottling machine is difficult. The development of a fluid flow model for a bottle with a complex shape can be aided by computational fluid dynamics (CFD). We previously proposed some solution searching algorithms for optimization problems using a CFD simulator [6], [7], [8].

Some motion curves (or cam curves) have proper names such as a modified sine or a modified trapezoid and are applied in machinery as standard cam curves even today. What is called a "universal cam curve" has six parameters or design variables and can express various curve shapes—including some of the standard cam curves mentioned above—by substituting any assignable values into the design variables [9], [10]. A motion curve, defined as a spline curve the control points of which are design variables, is optimized in order to satisfy requirements for desired mechanical characteristics [11], [12]. However, since the curves generated by using

the methods that define motion curves using a finite number of design variables also have finite flexibility, such methods may not provide the proper optimum motion curves. Thus, optimization methods, which can represent any shape of curve without design variables, are considered to be useful.

In the present study, we attempted to devise a motion curve optimization algorithm based on a genetic algorithm (GA). A GA is an optimization algorithm which can treat various forms of solutions such as continuous real numbers or discrete integer numbers. The proposed algorithm directly treats curves as solutions without design variables, by using the GA. We also propose genetic operations for motion curves. These are methods that can generate a new curve by numerically synthesizing several curves; even more complex curves could be created by applying the operations repeatedly.

The effectiveness of the proposed algorithm is demonstrated through optimization of a motion curve to decrease vibration at the surface of a liquid in bottles for a bottling machine.

II. MOTION CURVES

A. Overview of Motion Curves and Cam Curves

Assuming an object moves on a fixed path, the displacement s of the object from a default position along the path is expressed by the following equation as a function with respect to time t:

$$s = s(t). \qquad (1)$$

Such a function of displacement with respect to time is called a "motion curve" [1].

The term "cam curve" is used as a rough synonym of the motion curve. In general, a cam curve is a function expressing the motion of an object whose displacement s monotonically increases or decreases from 0 to the final displacement s_f during the time interval from 0 to the finish time t_f. Thus, the cam curve is a part of the motion curve, and the motion curve is composed of some cam curves and static conditions.

Now consider a nondimensional time $T = t/t_f$ and a nondimensional displacement $S = s/s_f$. A nondimensional cam curve is expressed as follows by applying T and S to (1):

$$S = S(T). \qquad (2)$$

This $S(T)$ is hereinafter simply called a cam curve.

In a broad sense the cam curve includes its first, second and third derivatives, and a set of the functions in (2) and

[1]K. Kanazawa and K. Yano are with Department of Mechanical Engineering, Mie University, Kurimamachiya-cho, Tsu-city, 514-8507, Japan `yanolab@robot.mach.mie-u.ac.jp`

[2]T. Nakada is with Shibuya Kogyo Co., Ltd., Mamedahon-machi, Kanazawa-city, 920-8681, Japan

(3) is called a "broadly-defined cam curve".

$$\begin{cases} V = V(T) = \dfrac{d}{dT}S(T) \\[2mm] A = A(T) = \dfrac{d^2}{dT^2}S(T) \\[2mm] J = J(T) = \dfrac{d^3}{dT^3}S(T), \end{cases} \qquad (3)$$

where $V(T)$ is the velocity curve, $A(T)$ is the acceleration curve, and $J(T)$ is the jerk curve.

A cam curve $S(T)$ whose velocity and acceleration are both 0 at $T = 0$ and $T = 1$ is called a "dwell-rise-dwell cam curve," and the condition of the curve is expressed as the following equation:

$$\begin{cases} S(T) = 0, \ V(T) = 0, \ A(T) = 0, \ \text{for } T = 0 \\ S(T) = 1, \ V(T) = 0, \ A(T) = 0, \ \text{for } T = 1. \end{cases} \qquad (4)$$

Since using a dwell-rise-dwell cam curve to convey an object is important from the perspective of vibration suppression, let us use the cam curve in this study.

B. Universal Cam Curves

A modified sine, a modified trapezoid, and some other standard cam curves are designed using sine curves and constants on an acceleration basis and are expressed by using a universal cam curve, which is a parametrically defined curve [9], [10]. The universal cam curve has six design variables, and can express various shapes of cam curves when values are put into the design variables. Here we used the universal cam curve to verify the effectiveness of the proposed algorithm in Section IV.

An outline of the universal cam curve is shown in Fig. 1. In the figure, A_{mp} and $-A_{\mathrm{mm}}$ are the maximum value and the minimum value of the acceleration curve, respectively. $T_1, T_2, \ldots, T_6$ are the design variables of the universal cam curve, and their domain is:

$$0 \le T_1 \le T_2 \le T_3 \le T_4 \le T_5 \le T_6 \le 1. \qquad (5)$$

The acceleration curve of the universal motion curve is defined as the following equation:

$$A(T) = \begin{cases} A_{\mathrm{mp}} \cdot \sin p_1(T), & \text{if } 0 \le T < T_1 \\ A_{\mathrm{mp}}, & \text{if } T_1 \le T < T_2 \\ A_{\mathrm{mp}} \cdot \cos p_3(T), & \text{if } T_2 \le T < T_3 \\ 0, & \text{if } T_3 \le T < T_4 \\ -A_{\mathrm{mm}} \cdot \sin p_5(T), & \text{if } T_4 \le T < T_5 \\ -A_{\mathrm{mm}}, & \text{if } T_5 \le T < T_6 \\ -A_{\mathrm{mm}} \cdot \cos p_7(T), & \text{if } T_6 \le T \le 1, \end{cases} \qquad (6)$$

where

$$p_i(T) = \frac{T - T_{i-1}}{\Delta_i}, \quad \text{for } i = 1, 3, 5, 7 \qquad (7)$$

and

$$\Delta_i = \begin{cases} \dfrac{2}{\pi}(T_i - T_{i-1}), & \text{for } i = 1, 3, 5, 7 \\[2mm] T_i - T_{i-1}, & \text{for } i = 2, 4, 6. \end{cases} \qquad (8)$$
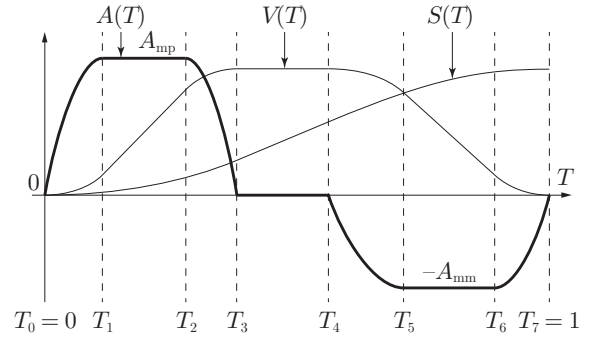

Fig. 1. Universal cam curve

A_{mp} and A_{mm} in (6) are obtained by solving the following system of equations:

$$\begin{cases} A_{\mathrm{mp}}\left(\Delta_1 + \Delta_2 + \Delta_3\right) = A_{\mathrm{mm}}\left(\Delta_5 + \Delta_6 + \Delta_7\right) \\ A_{\mathrm{mp}}\big\{\Delta_3^2 + 0.5\Delta_2^2 + \Delta_1^2 \\ \qquad + \Delta_3(1 - T_3) + \Delta_2(1 - T_2) + \Delta_1\big\} \\ \quad = A_{\mathrm{mm}}\big\{\Delta_7^2 + 0.5\Delta_6^2 + \Delta_5^2 \\ \qquad + \Delta_6(1 - T_6) + \Delta_5(1 - T_4)\big\} + 1. \end{cases} \qquad (9)$$

Eventually, the universal cam curve $S(T)$ is obtained as follows:

$$S(T) = \iint A(T)\,dT\,dT. \qquad (10)$$

III. THE MOTION CURVE OPTIMIZATION ALGORITHM

The proposed algorithm is a motion curve optimization algorithm based on a genetic algorithm (GA). A GA is a metaheuristic algorithm that mimics the process of the evolution of biological populations. This is also a flexible algorithm and can be applied to quite a wide range of problems. GAs treat the solutions for a problem as individuals and search for good solutions by repeatedly breeding new individuals through genetic operations. A standard GA optimizes a problem according to the following procedure:

1) Randomly generate the initial population of individuals.
2) Evaluate each individual in that population.
3) Stochastically select some pairs of individuals as parents according to their evaluated values.
4) Generate new individuals as children by giving genetic operations such as "crossover" and "mutation" to the parent individuals.
5) Evaluate these new individuals.
6) Go to 3) if termination conditions are not satisfied.

When the shapes of curves are optimized as in this study, the shapes are defined by design variables of real numbers in some way—such as a spline curve or a universal cam curve—and then this can be boiled down to an optimization problem of a function of real numbers. When the optimization problem of a function of real numbers is solved by using a GA, the individuals are expressed as real vectors and the genetic operations are defined as numerical processes among these vectors. Such a GA is called a "real-coded GA".

In contrast, in the proposed algorithm, the individuals are treated directly as curves. The differences between the proposed algorithm and the standard GA are the methods of generating the initial population and the genetic operations, which are explained as follows.

1) Initial Population: In the standard GA, the initial population is typically generated by substituting uniform random numbers to the design variables of each of the initial individuals. The proposed algorithm does not have a framework for generating the shape of a curve using design variables, and cannot be used with this method like the standard GA. However, since the algorithm treats a curve as an individual, arbitrary curves can be allocated to the initial population. Therefore, let the 16 dwell-rise-dwell cam curves described in reference [1] be the initial individuals in the algorithm. These cam curves have excellent or characteristic mechanical properties. They are listed in Table I. In addition, cam curve Nos. 3, 6, 7, 8, 14, 15 and 16 can be expressed using the universal cam curve.

2) Genetic Operation: The genetic operation of the proposed algorithm is defined as randomly-weighted summation of some curves as individuals.

Assuming that two selected curves as parent individuals are expressed as $S_{p1}(T)$ and $S_{p2}(T)$, the individual $S'_c(T)$ generated from these parent individuals using the crossover method is defined as follows:

$$S'_c(T) = f_c(T)S_{p1}(T) + \{1 - f_c(T)\} S_{p2}(T), \qquad (11)$$

where $f_c(T)$ is a function which decides the ratio of weight for combining the two curves, and let us call it a "crossover function." This crossover function is defined by the following equation as a linear function:

$$f_c(T) = R_{c1}T + R_{c2}(1 - T), \qquad (12)$$

where R_{c1} and R_{c2} are both normal random numbers with mean 0.5 and standard deviation σ_c. Let the standard deviation be $\sigma_c = 1$ as a standard. With this crossover method, the generated individual can efficiently combine both characteristics of two parent individuals as curves. In addition, since the crossover function $f_c(T)$ in (11) is a linear function, the generated individual $S'_c(T)$ is one higher-order curve than the parent individuals. Thus, a more complex curve can be generated by applying the crossover method repeatedly.

A child individual $S_c(T)$ is generated by a mutation of $S'_c(T)$ using a randomly-selected initial individual $S_i(T)$ and is defined by the following equation:

$$S_c(T) = R_m S_i(T) + (1 - R_m)S'_c(T), \qquad (13)$$

where R_m is a normal random number with mean 0 and standard deviation σ_m, and let σ_m be less than 1. Thus the mutation method adds or subtracts a bit of the characteristics of an initial individual to or from the individual generated by the crossover, and has the effect of promoting the genetic diversity of a population.

IV. VALIDITY VERIFICATION OF THE PROPOSED ALGORITHM

We verified the validity of the proposed algorithm by using a simplified optimization problem. The problem was optimized using the proposed algorithm and an existing algorithm in order to compare the performance of the two algorithms at searching for solutions.

We take the following vibration minimization problem of a dual pendulum-type sloshing model [13] as the simplified problem. A dual pendulum is a three-dimensional pendulum combined with two single pendulums; an outline drawing is shown in Fig. 2. The model simulates conveying the fluid in a bottle by the bottling machine described in Subsection V-A.

The model is conveyed along a circular path with radius R_w as shown in Fig. 2. $\theta(t)$ is a conveyance motion curve calculated by using (19) and (20) described later in this paper, $\phi(t)$ is the angle of the pendulum from the z-axis, and $\phi_x(t)$ and $\phi_y(t)$ are the angles of the projection pendulums to the x-z plane and y-z plane from the z-axis, respectively. $\phi(t)$ is calculated by the following equation using $\phi_x(t)$ and $\phi_y(t)$:

$$\phi(t) = \arctan \sqrt{\tan^2 \phi_x(t) + \tan^2 \phi_y(t)}. \qquad (14)$$

TABLE I

NAMES OF THE STANDARD DWELL-RISE-DWELL CAM CURVES

| No.	Cam Curves
1	Cubic
2	5th Power Polynomial
3	Cycloidal
4	Gutman F-3
5	Gutman F-5
6	Modified Trapezoid
7	Modified Sine
8	Modified Constant Velocity
9	Kubota Parabolic Sine
10	Jimbo Exponential
11	Unsymmetrical 4th Power Polynomial
12	Unsymmetrical 6th Power Polynomial
13	Unsymmetrical 7th Power Polynomial
14	Unsymmetrical Cycloidal
15	Ferguson IV
16	Makino Trapecloid
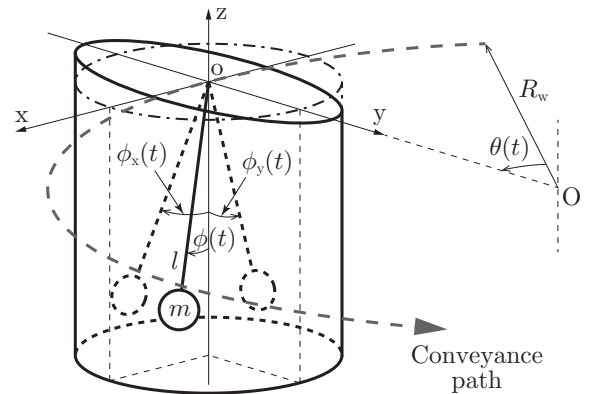
Fig. 2. Outline drawing of a dual pendulum-type sloshing model and its conveyance path

In addition, $\phi_x(t)$ and $\phi_y(t)$ are obtained by solving the following differential equations:

$$\begin{cases} \ddot{\phi}_x(t) = -\dfrac{R_w}{l}\ddot{\theta}(t)\cos\phi_x(t) - \dfrac{g}{l}\sin\phi_x(t) - \dfrac{c}{m}\dot{\phi}_x(t) \\ \ddot{\phi}_y(t) = -\dfrac{R_w}{l}\dot{\theta}(t)^2\cos\phi_y(t) - \dfrac{g}{l}\sin\phi_y(t) - \dfrac{c}{m}\dot{\phi}_y(t). \end{cases}$$
(15)

The names and the values of the other parameters in (20) and (15) are listed in Table II.

The optimization problem is defined by the following equation:

$$\text{Minimize } \max_{0 \le t \le t_c} |\phi(t)|.$$
(16)

We employed the method for representing a motion curve by using the universal cam curve mentioned in Subsection II-B and we applied the real-coded GA to optimize the curve as the existing algorithm for comparison with the proposed algorithm. For the comparison of the two algorithms under equivalent optimization conditions, the process of generating an initial population and the genetic operations for the algorithms were as follows.

Let the initial populations in the proposed algorithm be not the individuals listed in Table I but rather random individuals generated using the same method in the existing algorithm. In addition, let the genetic operations in the existing algorithm be the following method (similar to that of the proposed algorithm). Assuming the design variables of the universal cam curve are $\boldsymbol{T} = (T_1, T_2, \ldots, T_6)^{\mathrm{T}}$, the crossover is defined by:

$$\boldsymbol{T}'_c = \boldsymbol{R}_c\boldsymbol{T}_{p1} + (\boldsymbol{I}_6 - \boldsymbol{R}_c)\boldsymbol{T}_{p2},$$
(17)

and the mutation is defined by:

$$\boldsymbol{T}_c = \boldsymbol{R}_m\boldsymbol{T}_i + (\boldsymbol{I}_6 - \boldsymbol{R}_m)\boldsymbol{T}'_c,$$
(18)

where $\boldsymbol{T}_{p1}$ and $\boldsymbol{T}_{p2}$ are the parent individuals, $\boldsymbol{T}_c$ is the generated child individual, $\boldsymbol{T}_i$ is the initial individual selected randomly, $\boldsymbol{R}_c$ and $\boldsymbol{R}_m$ are 6-by-6 diagonal matrices whose diagonal elements are normal distributed with mean 0.5 and 0 and with standard deviation σ_c and σ_m respectively, and $\boldsymbol{I}_6$ is the 6-by-6 identity matrix. Other common parameters for both the algorithms are listed in Table III.

In order to verify the validity of the proposed algorithm, the problem defined above was optimized by each of the algorithms 1,000 times. The minimum, mean and maximum values of 1,000 optimum values of the proposed algorithm are 0.0620, 0.0921 and 0.1356 respectively, and those of the

TABLE II
MODEL PARAMETERS FOR CONVEYANCE OF THE DUAL PENDULUM

Length of pendulum: l	0.0082[m]
Gravitational acceleration: g	9.81[m/s^2]
Viscosity resistance per mass: c/m	0.05[s^{-1}]
Radius of circular path: R_w	0.45[m]
Final displacement: θ_f	0.35[rad]
Conveyance time: t_f	0.45[s]
Cycle time: t_c	1.5[s]

TABLE III
PARAMETERS FOR THE PROPOSED AND EXISTING ALGORITHMS

Number of generations	20
Population size	20
Number of elite individuals	10
Selection method	Tournament Sel. (Size: 2)
Standard deviations	$\sigma_c = 1$, $\sigma_m = 0.1$

existing algorithm are 0.0983, 0.1125 and 0.1683 respectively.

The theoretical optimum value of the problem should be comparable to the minimum optimum value 0.0620 of the proposed algorithm or less. The minimum optimum value 0.0983 obtained by the existing algorithm is markedly inferior to that of the proposed algorithm. This is because the existing algorithm can generate curves only within the framework of the universal cam curve and cannot express the theoretical optimum solution. In contrast, since the proposed algorithm can generate more complex curves by using the crossover method, it is understandable that the algorithm could obtain the neighborhood solution. Moreover, the proposed algorithm has better mean and maximum optimum values than those of the existing algorithm and has an advanced performance capacity for searching curves.

V. OPTIMIZATION OF MOTION CURVE FOR BOTTLE CONVEYANCE

A. Bottling Machine

An outline of the bottling machine used in this study is shown in Fig. 3. The machine is called an intermittent conveyance bottling machine, where "intermittent conveyance" indicates that the machine alternates conveyance and idling stages. A set of a conveyance stage and an idling stage is called an intermittent cycle. The machine conveys bottles along a circular path with radius $R_w = 0.45$[m] by rotating the wheel during the conveyance stages, and it caps the bottles during the idling stages. In this case, the machine fills three bottles with liquid simultaneously at every three intermittent cycles.

The rotational motion of the wheel of the machine is predefined as a motion curve. Let a reference motion curve supplied to the machine and the actual rotation angle of the wheel be $\theta_{\mathrm{ref}}(t)$ and $\theta(t)$, respectively, and the relationship between them is expressed as follows:

$$\mathcal{L}[\theta(t)] = \frac{1}{0.02s + 1}\mathcal{L}[\theta_{\mathrm{ref}}(t)].$$
(19)

Outlines of $\theta(t)$ and $\theta_{\mathrm{ref}}(t)$ during an intermittent cycle are shown in Fig. 4. The interval of time t between 0 and t_f is the conveyance stage, and the interval between t_f and t_c is the idling stage. Since the wheel has 18 pockets, the final displacement of the motion curve is $\theta_f = 20$[deg]. The reference motion curve $\theta_{\mathrm{ref}}(t)$ is described by the following equation by using a cam curve $S(T)$:

$$\theta_{\mathrm{ref}}(t) = \begin{cases} \theta_f \cdot S\left(\dfrac{t}{t_f}\right), & \text{if } 0 \le t < t_f \\ \theta_f, & \text{if } t_f \le t \le t_c. \end{cases}$$
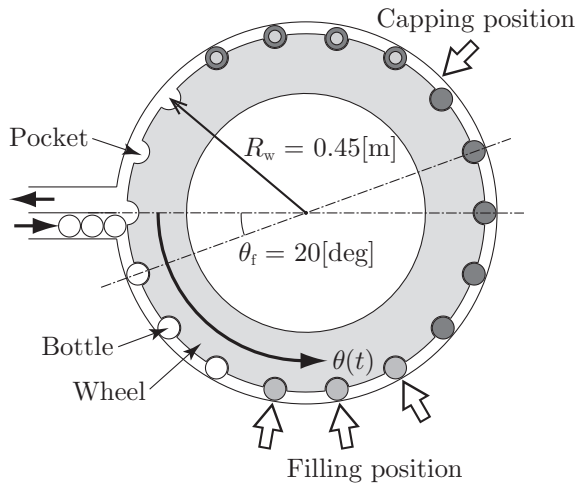(20)

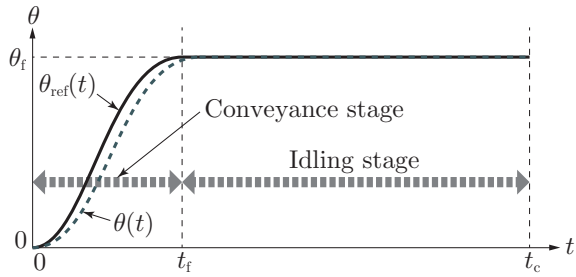Fig. 3. Outline drawing of the intermittent conveyance bottling machine

Fig. 4. Motion curve for the intermittent conveyance bottling machine

B. Formulation of Optimization Problem

In order to apply the proposed algorithm to the optimization of a conveyance motion curve for the bottling machine, we configured the setting for a CFD simulator and defined evaluation formulas and an optimization problem. In the optimization, let the target operational capability of the machine be 40 bottles per minute. In this case, the finish time of a conveyance stage is $t_f = 0.45[s]$ and the finish time of an idling stage or the cycle time is $t_c = 1.5[s]$.

An overview of the mesh setting for the CFD simulation is shown in Fig. 5. As seen in the figure, the mesh block as the analytical region covers only the upper part of the bottle since the fluidity of the lower part is low. The fluid used in the optimization is water at $20°C$, and the volume of the fluid is set to an amount that lets the surface of the liquid reach $0.02[m]$ from the top of the bottle. Conveyance of the bottle is simulated by applying virtual angular acceleration, which is the second derivative of a motion curve to the bottle, including gravitational acceleration of $-9.81[m/s^2]$ in the direction of the Z-axis.

In the optimization, the motion curve is evaluated by considering the maximum level $h_{max}(t)$ of the liquid with respect to time, and $h_{max}(t)$ is given by

$$h_{max}(t) = \max_{X,Y} h(X, Y, Z, t), \tag{21}$$

where $h(X, Y, Z, t)$ is the level of the liquid in each cell of
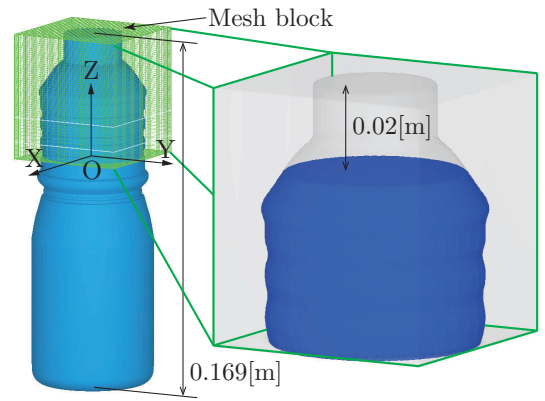

Fig. 5. Mesh setting for the CFD simulation and the rendering image

the mesh block at position (X, Y, Z) and time t. $h(X, Y, Z, t)$ is always constant regardless of Z if X, Y, and t are constant.

Let the maximum value H_1 of $h_{max}(t)$ in the whole cycle time be one evaluation value in order to suppress spilling the liquids from the bottles during the conveyance. In addition, let the maximum value H_2 of $h_{max}(t)$ during residual vibration after the conveyance be the other evaluation value in view of the next conveyance. H_1 and H_2 are expressed as the following equations:

$$H_1 = \max_{0 \leq t \leq t_c} h_{max}(t) \tag{22}$$

and

$$H_2 = \max_{t_r \leq t \leq t_c} h_{max}(t), \tag{23}$$

where t_r is the starting time of the estimation of H_2, and let it be $t_r = 0.6[s]$ in the optimization.

Finally, the optimization problem is defined by the following equation:

$$\begin{aligned} \text{Minimize} \quad & H_1(S(T)), \ H_2(S(T)) \\ \text{Subject to} \quad & \min_{0 \leq T \leq 1} \dot{S}(T) \geq 0. \end{aligned} \tag{24}$$

This is a multiobjective optimization problem, which has two objective functions or evaluation functions. In order to solve the problem, we applied combination of the proposed algorithm and NSGA-II [14], which is one of the most commonly used multiobjective genetic algorithms, to the problem. The parameters for the algorithm are listed in Table IV.

C. Optimization Result

The broadly-defined cam curves of the optimized motion curve and the modified sine are shown in Fig. 6. Since the

TABLE IV

PARAMETERS FOR THE OPTIMIZATION ALGORITHM

Number of generations	50
Population size	36
Selection method	Crowded Tournament Sel.
Crossover method	Proposed Algorithm
Mutation method	Proposed Algorithm
Standard deviations	$\sigma_c = 1, \ \sigma_m = 0.1$

modified sine has excellent properties and is commonly applied to actual bottling machines, we adopted it as a standard for comparison with the optimized motion curve. In addition, the waveform of each $h_{\max}(t)$ as calculated with (21) are shown in Fig. 7. The evaluation values of the optimized motion curve are $H_1 = 0.0070[\text{m}]$ and $H_2 = 0.0014[\text{m}]$, and those of the modified sine are $H_1 = 0.0093[\text{m}]$ and $H_2 = 0.0042[\text{m}]$.

The acceleration graph in Fig. 6 shows that the optimized motion curve has a complex shape, which could not be expressed by the universal cam curve shown in Fig. 1. However, as shown in Fig. 7, the amplitude of vibration of the liquid in the case of the optimized motion curve during conveyance is smaller than that of the modified sine and the optimized motion curve exhibits almost no residual vibration after conveyance. Therefore, the result shows that the proposed algorithm can obtain optimized curves which cannot be expressed by other existing methods.

In addition, we performed experiments by using the actual intermittent conveyance bottling machine. The result showed that conveyance with the optimized motion curve could reduce vibration at the surface of a liquid, in accordance with the simulation results.

VI. CONCLUSIONS

We constructed an optimization algorithm for motion curves based on a genetic algorithm. The advantages of the algorithm are as follows.

1) A quick optimization with relatively few analyses of individuals is possible by setting up some existing curves with good properties as the initial individuals.
2) Motion curves with a lot of flexibility can be generated by using the proposed genetic operations repeatedly.
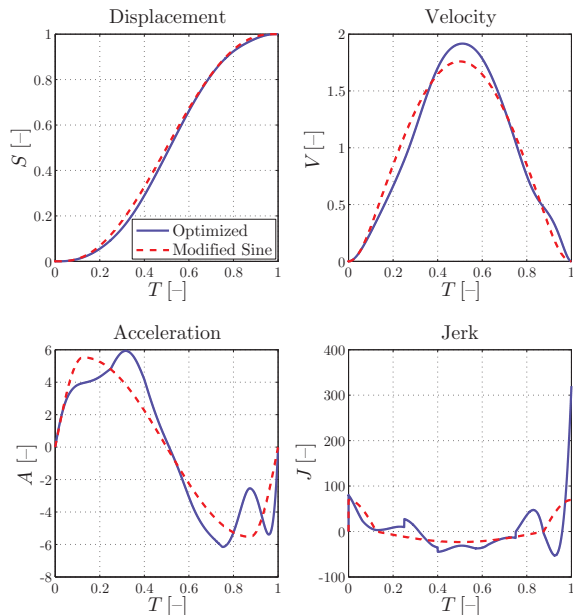

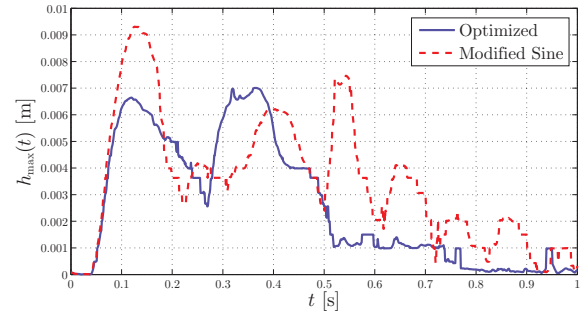Fig. 6. Broadly-defined cam curves of the optimized motion curve and the modified sine

Fig. 7. Maximum liquid level waveforms for the optimized motion curve and the modified sine

Moreover, motion curves for bottle conveyance of an actual bottling machine were optimized using the proposed algorithm. As a result, an optimized motion curve with a complex shape, which could not be generated by standard GAs, was obtained and can reduce vibration at the surface of the liquid for a bottling machine.

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