Optimal Tolerance Assignment with Automatic Feature Detection

التوزيع الأمثل للتجاوزات مع التعرف على السطح المشغل آلياً

I.M. Elewa **A.A. Abdel-Shafi** **K.A. Kamal**

Associate Prof. *Associate Prof.* *Research Assistant*

Indust. Prod. Eng. Dept., Faculty of Eng., Mansoura Univ.

الملخص العربي

في هذا البحث تم تطوير طريقة جديدة لتوزيع التسامحات للأجزاء المكونة للتجميعات الميكانيكية بحيث تفي بالمتطلبات الوظيفية وفي نفس الوقت تعمل على تقليل تكلفة الإنتاج. وقد تم استخدام الحاسب الألي في النظام الجديد وذلك لتوفير الوقت والجهد المستهلك في الحسابات والبحث في الجداول والكتب. والبرنامج الذي تم تطويره له امكانية الاتصال بالبرامج المستخدمة في التصميم والرسم واستخلاص البيانات اللازمة لتشغيله وقد تم تطبيقه بنجاح مع البرامج المستخدمة في الرسم والتصميم مثل الأتوكاد. وأيضاً له القدرة على الاتصال بالبرامج المستخدمة في التصنيع وارسال البيانات الازمة لتشغيلها. ولذلك يمكن أن يعتبر هذا البرنامج مساهمة في تقليل الفجوه بين البرامج المستخدمة في التصنيع والتصميم.

Abstract

Tolerance analysis is used for an optimal tolerance assignment to satisfy the function requirements, and mean while minimizes production cost. This paper introduces a computerized procedure for optimal tolerance assignment in mechanical assemblies to satisfy the function dimensions.

The developed computer system has the ability to integrate CAD systems which support DXF (Drawing Interchange File). For example, the software receives a DXF file of an assembly then analyzes it to detect the individual parts of the assembly using rules of form definitions in system knowledge base. Also, the developed system estimates the dimensions and the type of chain link for each part to generate the tolerance chain link relation. The optimization problem is formulated automatically with tolerance-cost functions as an objective function to be minimized. The constrains are the limits of function dimensions and process capability boundaries. Then, the program generates M. file which used by MATLAB package to calculate the optimal tolerance values. A mechanical assembley case study is used as an applicaton to show the capability of the new system

Keywords

Automatic dimensioning, Tolerancing, DXF format, Pattern recognition, Form defination.

1 Introduction

A strong dependence exists between design tolerances and manufacturing costs. Therefore cost is used as the key in performing tolerance distribution [1]. A particular tolerances selection implies a certain cost in manufacturing. Reduction of cost is possible by increasing tolerances but such an increase must be constrained by some performance measure (such as functionality and interchangability). A great deal of tolerance researches [2, 3, 4] on toleranceing have been devoted to the resolution of trade-off between cost and performance. However, they are concerned with tolerance analysis, that is for a given set of tolerances, find the effect on cost or performance. It should be noted that tolerance is an input to the analysis. If a particular combination of tolerances does not meet the criteria, some or all of the input have to be changed and, the procedure iterates. In an interactive mode, input preparation depends on the "experience" of the user but, there can be (infinitely) many input combinations to choose from. Hence, there is no assurance of convergence, rather than mentioning optimality. Now, Mont. Carlo simulation is preferred in a more than one resource [5]. While with simulation, the solution be made arbitrarily close to the optimum, thus the amount of resource demanded also can be arbitrarily large. The synthesis of tolerance, an alternative to manual data preparation and random number generation, remained as an intellectual and practical challenge. Recently, tolerance synthesis by nonlinear optimization has been used. Tolerance is treated as continuous variable its relationship to cost take the form of a continuous function such as the one illustrated in Fig. 1.

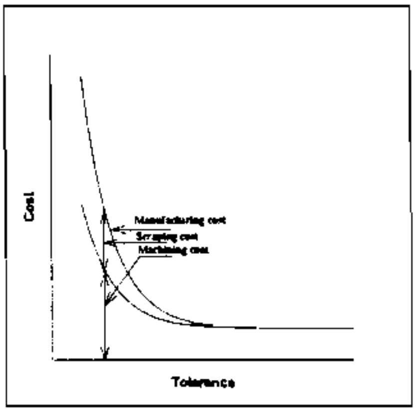

Figure 1. Cost Model for a Single Process

2. Cost Model for a Single Process

A cost model for a single process means a plot of the manufacturing cost as a function of machining precision under the assumption that the same process has to be used independently of the precision requirements. A cost model for a single process is shown in Fig. 1. The single process means in this research the finishing process for producing the product.

As it can be seen in Fig. 1, Manufacturing cost may be divided into two parts namely :

1. Machining cost
2. Scrapping cost

Machining cost cover the actual time used to produce a complete acceptable basic element, including setup cost, tools depreciation cost, inspection time cost, etc. This cost component increase as the tolerances are narrower, since narrow tolerances need additional setups, additional operations, more expensive measuring services etc.

Scraping cost occurs when a part falls outside the specified tolerance. The scraping cost part consists of two components either the cost of repairing the part concerned, or the cost of the part as a whole if it has to be reject. As long as the specified tolerance is wide compared to the process capability, scraping cost is negligible, but as soon as the specified tolerance is narrow than the process capability, then the scrapping cost will increase rapidly. It is important to notice that, if the cost of the process (reworking) is higher than the cost of raw material then the product will be scarped.

3. Cost Minimization as an Objective Function

Cost minimization is chosen as the objective function for the following reasons [6]:

Firstly, the planer must design a manufacturing plan that results in a component that is not only functionally correct but also suitable for manufacture at low cost. Tolerance play a very important rule in cost, therefore cost is the key to good tolerance allocation.

Secondly, many of tolerance allocation methods are done by rule of thumb. The purpose of many objectives is to obtain the least possible scrap percentage, because the quantity of scrap is assumed to be proportional to cost. However, it does not necessarily follow that the bigger the scrap percentage the higher the cost. Cost depends not only on scrap percentage, but also on the machining, tooling, etc., expenses of each operation.

Thirdly, although there are many other manufacturing criteria, such as maximum profit, maximum quality gain, maximum rate of return and maximum benefits, etc. most of them are difficult to relate to tolerance, therefore cost is the more common and easy criterion.

4. Mathematical Models For Production Cost-Tolerance

A review of mathematical models for production cost-tolerance shows that all of them using imperical cost data [7, 8] of production processes. These processes include: turning on lathe, face milling, drilling and hole machining (true position), rotational surface and internal grinding, as well as die, sand and investment casting. The empirical cost-tolerance data curves used in this research are illustrated and plotted in Fig. 2. In practice, the empirical cost-tolerance data should be directly obtained from machine shops through experiments or observations, and recorded in the original form of discrete points. It is assumed that the empirical data curves are composed of many closely-placed data points, rather than results of interpolation or curve fitting. Discrete data points are picked up from these curves to direct model fitting and fitting error analysis.

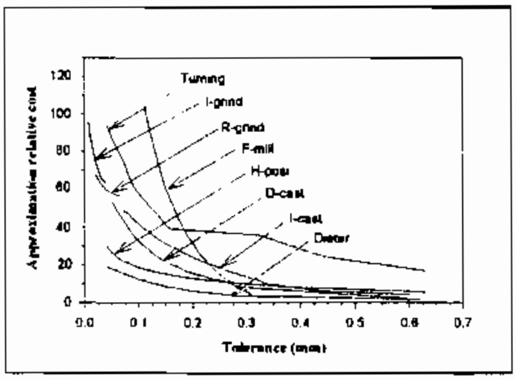

Figure 2. Empirical production cost-tolerance curves

In formulation the optimal tolerance design problem, different production cost-tolerance model were introduced to represent the empirical production cost-tolerance relations, such as the one shown in Fig. 2. This existing models include :

- Exponential model (Exponent) by Speckhart [9],

$$g(TD) = C_0 \; e^{-C_1 TD} \qquad (1)$$

Where : TD tolerance

g(TD) Cost tolerance %

- Reciprocal squared model (R-Squared) by Spots [10],

$$g(TD) = C_0 TD^{-2} \quad (2)$$

- Reciprocal powers model (R-Power) by Sutherland and Roth [11],

$$g(TD) = C_0 TD^{-C_1} \quad (3)$$

- Reciprocal powers and exponential hybrid model (RP-E Hybrid) by Michel and Siddall [12],

$$g(TD) = C_0 TD^{-C_1} e^{-C_1 TD} \quad (4)$$

- Reciprocal model (Recip.) by Chase and Greenwood [13],

$$g(TD) = C_0 TD^{-1} \quad (5)$$

- Modified exponential model (M-Exponent) by Dong and Soom [14],

$$g(TD) = C_0 e^{-C_1 (TD - C_2)} + C_3 \quad (6)$$

- Discrete model (discrete) by Lee and Woo [15].

The above existing production cost-tolerance models were used in different optimal tolerance design formulations. They can provide quantitative measures of the production cost-tolerance relations However, it has been recognized that updated and more complete production tolerance data, and better mathematical models to represent the actuality of these data, are necessary [4, 14, 15].

The previous types of mathematical models have been tested using the eight representative cost-tolerance curves. Six modified mathematical models for cost-tolerance relations are adopted from many candidates [16]. These six models all present a better fit to the empirical cost-tolerance data [17]. These modified models consist of two major classes: hybrid models and polynomial models.

4.1 Hybrid Model

- Combined Reciprocal Powers and Exponential Function (Combined RP-E*)

$$g(TD) = C_0 + C_1 TD^{-C_2} + C_3 e^{-C_4 TD} \quad (7)$$

- Combined Linear and Exponential Function (Combined L-E*)

$$g(TD) = C_0 + C_1 TD + C_2 e^{-C_3 TD} \quad (8)$$

- B-Spline Curve (B-Spline*)

$$g(TD) = C_0 B_1^4 (TD) + C_1 B_2^4 (TD) + C_2 B_3^4 (TD) + C_3 B_4^4 (TD) + C_4 B_5^4 (TD) \quad (9)$$

4.2 Polynomial Model

- Cubic Polynomial (Cubic-P*)

$$g(TD) = C_0 + C_1 TD + C_2 TD^2 + C_3 TD^3 \quad (10)$$

- Fourth Order Polynomial (4th-P*)

$$g(TD) = C_0 + C_1 TD + C_2 TD^2 + C_3 TD^3 + C_4 TD^4 \qquad (11)$$

- Fifth Order Polynomial (5th-P*)

$$g(TD) = C_0 + C_1 TD + C_2 TD^2 + C_3 TD^3 + C_4 TD^4 + C_5 TD^5 \qquad (12)$$

The combined reciprocal powers and exponential function, and the combined linear and exponential function models are introduced, by adding a reciprocal powers term or a linear term to the original exponential model, to improve approximation of the exponential function to the empirical data at the right tolerance zone. The polynomial functions of cubic, fourth and fifth orders and the B-spline function are introduced to find the best representation of an empirical data curve.

The model parameters, , have been determined using least square approximation. The calculation model C_i parameters of these models are listed in Table 1.

In Table 1, The cost-tolerance models are arranged according to the number of their model parameters to illustrate the influence of the number of model parameters to the fit. The average fitting errors of the eight empirical data curves are also given in Table 2. The minimum average relative errors of the best performed model is highlighted.

From Table 2, the mathematical models (equations 7, 8, 9, 10, 11 and 12), for production cost-tolerance relation fit various empirical production data with considerably less modeling error, is apparent.

The model selection can be performed using the a knowledge-base system based on less model error. An intelligent computer system, rather than the designer, can automatically create the objective function for optimization. This work has provided better production cost-tolerance models and the above explicit guidelines for applying the previous models.

5 Optimal Tolerance Design Using Production Cost-Tolerance Models

The previous production cost-tolerance models are combined with the tolerance synthesis formulation for both an independent dimension chain [14], and for general multiple dimension chains [4], to produce a new method for tolerances assignment in mechanical assembly.

5.1 Brief Outline of Method

This section gives an introduction to the analytical approach and illustrates what can be accomplished by the new method, what inputs are required. The mathematical problem of finding the optimum tolerance set is somewhat complex and is outlined in the following section.

In order to successfully use the method, it is necessary to cover the following points

1- A fundamental equation which is a mathematical description of the critical dimensions [18].
2- Tolerances on these critical dimensions, TD_i (constrain)
3- Data relating the relative costs of holding each dimension as a function of the tolerance as an objective function, $G(TD_1, \ldots\ldots TD_p)$ (from section 4).
4- Production process for producing each part in the chain and estimates the process capabilities , TD_{min}.(constrains)

Table 1. Calculated optimal model parameters $C_0, C_1, \ldots$

Mathematical Models		Empirical Cost-Tolerance Curves							
		Dieter	D-cast	I-cast	H-posi	F-mill	Turning	R-grind	I-grind
R-squared	C_0	1.574E-2	4.898e-2	0.1843	2.765E-2	0.6095	0.4952	1.822E-2	1.069E-5
Recip	C_0	0.6470	1.966	3.110	1.161	6.756	5.682	1.422	0.4677
Exponent	C_0	22.49	7.11	73.31	27.81	431.5	66.43	71.24	98.87
	C_1	7.210	9.339	6.903	3.661	17.64	2.738	4.348	18.39
R-Power	C_0	1.657	3.515	3.637	5.376	1.463	14.47	57.39	32.51
	C_1	0.6999	0.8162	0.9351	0.4916	1.656	0.5582	0.1441	0.1932
RP-E Hybrid	C_0	11.99	18.25	33.28	6.066	434.2	59.83	37.78	38.22
	C_1	0.1733	0.3888	0.1060	0.4611	1.109E-4	4.206E-2	0.1412	9.41E-7
	C_2	5.475	-4.969	6.154	0.3658	18.23	2.382	1.175E-2	10.34
Combined L-E*	C_0	0.3956	3.782	1.0E-5	8.052	1.0E-5	1.0E-5	53.54	56.37
	C_1	1.929	1.0E-5	1.0E-5	1.0E-5	1.0E-5	1.0E-5	51.11	0.8113
	C_2	23.94	87.43	73.94	30.87	449.9	67.30	32.77	51.17
	C_3	8.792	12.36	6.872	12.09	18.13	2.590	54.25	73.33
Cubic-P*	C_0	22.56	75.78	71.32	35.05	322.1	66.05	86.83	106.8
	C_1	-158.9	-6.343E2	-4.307E2	-2.367E2	-3.734E3	-1.725E2	-1.684E3	-3.399E3
	C_2	411.0	1.968E3	1.006E3	7.160E2	1.488E4	2.535E2	3.675E4	9.155E4
	C_3	-359.3	-2.071E3	-8.547E2	-7.168E2	-2.034E4	-1.862E2	-2.925E5	-9.103E5
Combined RP-E*	C_0	5.341E-3	1.0E-5	1.0E-5	1.0E-5	1.0E-5	5.228E-3	39.03	45.36
	C_1	1.319	1.023	0.2533	5.126	1.0E-5	0.3600	17.90	10.94
	C_2	1.0E-5	0.9258	0.7776	0.4475	1.836	0.9044	1.0E-	1.0E-5
	C_3	23.21	44.80	72.17	6.652	455.3	61.39	30.84	51.19
	C_4	9.308	8.613	7.021	11.72	18.24	2.531	63.47	73.00
4th Order B-Spline*	C_0	23.11	73.78	73.30	35.46	372.1	71.56	86.83	106.8
	C_1	-3.995	-29.94	-2.620	-5.674	-300.1	26.61	-193.7	-459.6
	C_2	13.70	86.56	30.66	40.89	935.7	44.23	5.366E3	1.366E4
	C_3	-19.60	-176.5	-61.80	-56.29	-3.038E3	-27.37	-1.730E5	-3.964E5
	C_4	1.836E5	0.0	6.485E5	5.595E5	0.0	54.32	0.0	0.0
4th-P*	C_0	23.91	87.31	79.44	36.71	280.7	83.7	95.70	104.2
	C_1	-188.2	-1.091E3	-6.226E2	-3.479E2	-2.407E3	-4.591E2	-3.066E3	-2.216E3
	C_2	644.7	5.336E3	2.533E3	1.620E3	2.823E3	1.652E3	1.111E5	-7.455E4
	C_3	-1.029E3	-1.272E4	-4.448E3	-3.558E3	4.596E4	-2.737E3	-1.949E6	7.949E6
	C_4	628.1	1.101E4	3.225E3	2.510E3	-1.061E5	1.546E3	1.04E7	-3.585Ex
5th-P*	C_0	23.82	97.17	86.55	42.01	11.08	112.3	98.86	104.4
	C_1	-1.847E2	-1.461E3	-8.407E3	-4.827E2	8.506E3	-1.060E3	-3.687E3	-2.335E3
	C_2	6.028E2	1.112E4	4.543E3	3.252E3	-1.645E5	5.833E3	1.168E5	-5.045E4
	C_3	-8.282E2	-4.331E4	-1.397E4	-1.134E4	1.215E6	-1.534E4	-3.336E6	5.852E6
	C_4	2.093E2	8.126E4	2.176E4	1.934E4	-4.033E6	1.845E4	3.919E7	-7.690E7
	C_5	3.139E2	-5.820E4	-1.328E4	-1.275E4	5.031E6	-8.269E3	-1.647E8	-1.169E9

Table 2. Fitting errors of cost-tolerance models (%)

Math Models	Tolerance Zone	Empirical Cost-Tolerance Curves								Average Errors
		Dieter	D-cast	I-cast	H-posi	F-mill	Turning	R-grind	I-grind	
R-squared	overall	74.3	64.6	56.5	76.3	20.4	52.3	61.5	81.3	71.5
	tigth	51.9	40.3	29.3	53.5	14.9	26.9	61.5	82.3	76.0
(Np=1)	medium	90.3	88.3	68.8	92.0	27.0	51.5	-	-	68.7
	loose	95.3	88.2	68.7	98.1	-	87.7	-	-	87.0
Recip	overall	29.4	22.6	20.6	38.5	48.2	26.9	31.7	50.3	47.4
	tigth	28.4	15.7	9.50	21.0	22.7	18.8	31.7	50.3	46.0
(Np=1)	medium	32.9	24.7	15.8	47.2	79.3	35.9	-	-	56.4
	loose	16.3	95.9	56.5	65.7	-	44.8	-	-	86.1
Exponent	overall	9.05	12.4	4.54	14.0	9.84	10.9	1.35	2.01	7.48
	tigth	3.39	10.3	2.94	10.6	5.39	9.06	1.35	2.01	4.73
(Np=2)	medium	7.90	13.1	3.80	12.9	15.3	8.86	-	-	14.0
	loose	45.5	33.7	20.9	28.0	-	23.8	-	-	37.0
R-Power	overall	22.48	19.3	20.7	2.51	24.4	12.9	0.510	1.87	12.3
	tigth	16.1	8.06	7.66	2.49	12.0	0.360	0.510	1.87	5.33
(Np=3)	medium	19.4	18.7	14.6	1.87	39.5	10.5	-	-	26.6
	loose	67.1	198	155	4.51	-	46.0	-	-	79.2
RP-E Hybrid (Np=3)	overall	6.79	3.50	4.01	1.84	8.67	9.79	0.498	0.909	4.81
	tigth	3.43	1.47	1.55	1.46	5.49	6.31	0.498	0.909	3.60
	medium	5.54	3.53	7.96	1.62	12.3	7.83	-	-	9.53
	loose	28.6	34.5	28.2	3.66	-	25.6	-	-	28.1
Combined L-E* (Np=4)	overall	1.54	10.8	4.38	4.21	8.86	9.73	0.303	0.359	5.19
	tigth	1.03	7.14	2.88	3.08	5.33	6.73	0.303	0.359	3.64
	medium	1.59	9.94	3.45	4.11	12.9	88	-	-	10.7
	loose	3.60	79.6	22.2	8.04	-	24.2	-	-	29.5
Cubic-P*	overall	3.20	12.9	4.38	5.50	7.01	6.67	0.242	0.302	4.56
	tigth	3.00	10.6	3.28	5.34	3.58	8.27	0.242	0.302	2.56
(Np=4)	medium	3.60	32.1	3.48	5.12	11.2	5.89	-	-	9.73
	loose	11.2	60.1	19.8	7.15	-	8.32	-	-	17.5
Combined RP-E* (Np=5)	overall	3.43	4.38	4.46	3.36	8.64	9.75	0.261	0.359	4.32
	tigth	1.67	1.87	2.79	0.929	5.43	5.79	0.261	0.359	2.15
	medium	3.25	4.01	3.71	0.928	12.5	8.00	-		9.20
	loose	12.4	47.4	21.3	4.02	-	25.2	-		26.4
4th Order B-Spline* (Np=5)	overall	2.61	12.9	3.90	5.12	4.85	6.06	0.242	0.172	6.37
	tigth	7.88	10.6	3.06	5.04	3.11	6.47	0.242	0.172	3.07
	medium	3.10	12.1	3.38	5.07	6.97	5.55	-	-	10.7
	loose	8.31	60.3	13.8	5.60	-	8.11	-	-	25.0
4th-P*	overall	1.08	7.33	2.41	3.33	5.36	5.76	0.149	0.172	3.14
	tigth	0.574	5.80	1.68	2.79	2.35	4.93	0.149	0.172	1.50
(Np=5)	medium	1.04	7.01	2.33	3.43	8.59	5.38	-	-	7.33
	loose	3.58	34.9	7.25	4.67	-	9.08	-	-	12.2
5th-P*	overall	0.870	3.60	1.73	1.76	3.06	4.62	0.109	0.168	2.02
	tigth	0.497	2.43	0.702	1.24	0.728	2.44	0.109	0.168	0.671
(Np=6)	medium	1.03	3.78	1.50	1.68	5.90	4.37	-	-	5.04
	loose	1.74	18.7	9.55	3.73	-	9.35	-	-	10.8

5.2 Initial Tolerance Distribution

The procedure of initial tolerance distribution as follow [18]:

1. Analyze the function of the assembly, and determine the functional requirements; that is determine the tolerance of the sum dimension in the chain concerned (TD_Σ).

2. Determine the dimensions that influence the sum dimension and identify the variables, $D_1, D_2, \ldots\ldots, D_n$
3. Determine the fundamental equation of the sum dimension.
   $D_\Sigma = f(D_1, D_2, \ldots, D_n)$
4. Compute the scaling factors (A_i).
5. Classify the chain links.
6. Determine the desired confidence level
7. Determine the normalized tolerance TW_Σ
8. Determine the links that have predetermined tolerances and the ones have determinable tolerances
9. The tolerances are proportional to the corresponding dimensions and get form :

$$TD_i = \frac{ED_i\, TD_\Sigma}{1.4\sqrt{\sum_{i=1}^{n} ED_i^{\,2}}} \qquad (13)$$

Where ED Expectation of a dimension D

10. From TD_i get IT grade, from IT grade and the form of the individual part determine the production process for each dimensions in the chain.
11. Determine the expectation of the individual dimension in such a way the following equation is satisfied

$$ED_\Sigma = \sum_{i=1}^{n} A_i(MD_i + TD_i(EZ_i - 0.5)) \qquad (14)$$

Where MD is the distance to the middle of tolerance zone

5.3 Formulation of Optimal Tolerance Design.

- The formulation of optimal tolerance design for an independent dimension chain can be represented as follows:

$$\min_{w.r.t.\,TD} G\ (TD,\ldots\ldots TD_n) = \min_{w.r.t.\,TD_i} \sum_{i=1}^{n} g(TD_i) \qquad (15)$$

subject to,

- For worst case condition, the following sure-fit formula will insure the clearance to be within the desired

$$TD_1 + TD_2 + \ldots\ldots\ldots + TD_n = TD_\Sigma \qquad (16)$$

- For statistical basis, the following expression must hold:

$$TD_1^{\,2} + TD_2^{\,2} + \ldots,\ldots\ldots + TD_n^{\,2} = TD_n^{\,2} \qquad (17)$$

- And

$$TD_{min,i} < TD_i < TD_{max,i} \quad (i = 1, \ldots\ldots, n) \qquad (18)$$

Where

$TD_i . \quad . TD_n$ - n components tolerances of the dimension chain,

TD_Σ-the resultant (or assembly)tolerance or design requirement.
TD_{min}- and TD_{max} are the bounds of process capability.

$G(TD_1,......,TD_n)$-the total production cost for all mechanical features associated with the adjustable design tolerances. The sum of production costs for the mechanical features are specified by adjustable tolerances. $TD - TD_n$.

6. Program Outline

One of the main objective of this research is to develop a computer program of optimal tolerance distribution for parts in mechanical assembly to keep the function dimension on acceptable limits and keeps cost as minimum as possible. The software uses the models introduced in (2) (Model for individual parts and Model for sum dimension) to get initial solution for the problem, then generates M. file for MATLAB software to get the optimal tolerance values for individual parts in the assembly.

6.1 Program Flow Chart

Flow chart for the new system is illustrated in Fig. 3.

The inputs of this system are:

- No. of link in the chain (K).
- Nominal Dimension of each part in the chain (D)
- The geometrical shape (Form) for each part in the chain.
- The type of chain links (TCL).
- Scaling factor for each link in the chain (A).
- The function dimension (DS).

This data can be entered to the program using TDF file which has a special format. TDF file may be written by an ASCII editor or using the help screen in the program The data can be entered to the program by a DXF (drawing interchange files) files which are generated from numerous CAD systems. DXF files are standard ASCII text files which contain complete details for the drawings. The program uses rules, in its knowledge base, to translate DXF file into TDF file. The system receives a DXF file and analyzes this file to determine the individual parts in the assembly. The user of this system , in this situation, inputs the scaling factor only (Fig. 4).

Every shape must be defined by lines, circles, arc, etc. , for example (Fig. 5. a):

The part is a bush if :-

line (X,Y,X1,Y),
line (X1,Y1,X2,Y1),
line (X,Y2,X2,Y2),
line (X,Y3,X2,Y3),
line (X1,Y4,X2,Y4),
line (X,Y5,X1,Y5),
line (X,Y,X,Y5),
line (X1,Y,X1,Y1),
line (X1,Y4,X1,Y5)
line (X2,Y1,X2,Y4),
circle (Xc,Yc,R1), R1= (Y2-Y3)/2,
circle (Xc,Yc,R2), R2= (Y1-Y4)/2,
circle (Xc,Yc,R3), R3=(Y-Y5)/2.

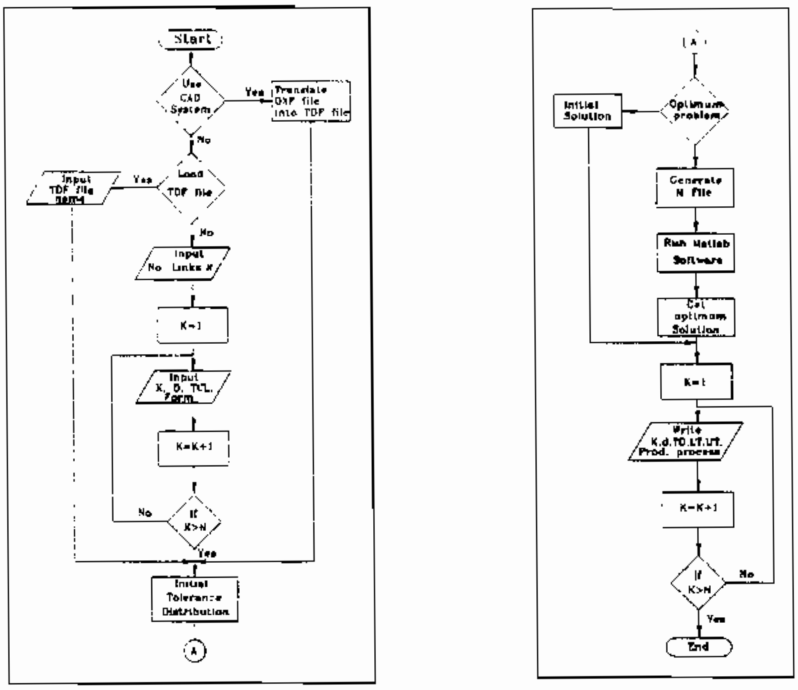

Figure 3. Program flow chart.

And so on for every shape, but it is important to notice, the effect of the part position therefore, if the previous bush is rotated 90 degrees there is another definition for this bush. The definition will be (Fig. 5.b):

The part is a bush if :-

line (X,Y,X5,Y),
line (X,Y1,X1,Y1),
line (X4,Y1,X5,Y1),
line (X1,Y2,X4,Y2),
Line (X,Y,X,Y1),
line (X1,Y1,X1,Y2),
line (X2,Y,X2,Y2),
line (X2,Y,X3,Y2),
line (X4,Y1,X4,Y2),
line (X5,Y,X5,Y1),
circle (Xc,Yc,R1), R1= (X3-X2)/2,
circle (Xc,Yc,R2), R2= (X4-X1)/2,
circle (Xc,Yc,R3), R3=(X5-X)/2.

Therefore, The new system has a knowledge base contains rules to define the most common parts which is used in mechanical assembly in several positions.

7. Case Study Example

A mechanical assembly that is shown in Fig. 6. The gap is the sum dimension . In order to function properly, the gap must, on the one hand, be larger than zero (to preveut jamming), on the other, be less than a certain value (to prevent axial motion of the gears). The following values are assumed :

$D_1 = 5$ mm $D_2 = 5$ mm
$D_3 = 79$ mm $D_4 = 40$ mm
$D_5 = 50$ mm

The gap must be kept ($0 < D_\Sigma < 0.18$ mm)

7.1. Model Solution

7.1.1 Manual Procedure

1- Fundamental equation is

$D_\Sigma = D_4 + D_5 - D_1 - D_2 - D_3$

2- The tolerances for function dimension is :

$TD_\Sigma = 0.18$ mm

3- Production process (from section 5.2) for each part in the chain are

D_1, D_2 : Grinding,

D_3 = Turning,

D_4 = D5 = Internal Ginning

4- Initial solution (equation 13) are obtained:

X_0=[0.0063 0.0063 0.0996 0.0504 0 0631]

From Table 2, the-cost tolerance model for each part is .

For each D1, D_2 , the model is fifth order polynomial (5th-P*).

For D3, the model is reciprocal powers (R-Power).

For D_4 . the is fifth order polynomial (5th-P*).

For D_5, the is fifth order polynomial (5th-P*).

The total objective function is

g(TD)=320.4+(-3687)*X(1)+(156800)*X(1)^2+(-3536000)*X(1)^3+
(39190000)*X(1)^4+(-164700000)*X(1)^5+(-3687)*X(2)+
(156800)*X(2)^2+(-3536000)*X(2)^3+(39190000)*X(2)^4+
(-164700000)*X(2)^5+(14.47)*X(3)^(-1*(0.5582))+
(-3687)*X(4)+(156800)*X(4)^2+(-3536000)*X(4)^3+(39190000)*X(4)^4+
(-164700000)*X(4)^5+(-184.7)*X(5)+(602.8)*X(5)^2+
(-828.2)*X(5)^3+(209.5)*X(5)^4+(313.9)*X(5)^5;

The constrains are

a - The sum dimension and individual parts (equation 17) :

TD(1)^2+TD(2)^2+TD(3)^2+TD(4)^2+TD(5)^2=0.18^2

b - The process capability for each production process (equation 18) :

VUB =[0.012 0.012 0.074 0.052 0.39]

VLB =[0.005 0.005 0.03 0.011 0.1]

4- Initial solution (equation 13) are obtained:

X_0=[0.0063 0.0063 0.0996 0.0504 0.0631]

Then the optimization problem is solved using Computer package and the solution are:

TD_1 = 0 0120 mm,

TD_2 = 0.0120 mm,

TD_3 = 0.0740 mm,

TD_4 = 0.0496 mm,
TD_5 = 0.1044 mm
According equation (14)
The Dimensions with its tolerance will be (model solution).

$D_1 = 5^{\pm 0.006}$ mm, $D_2 = 5^{\pm 0.006}$ mm

$D_3 = 79^{\pm 0.037}$ mm, $D_4 = 40^{\pm 0.025}$ mm

$D_5 = 50^{\pm 0.051}$ mm

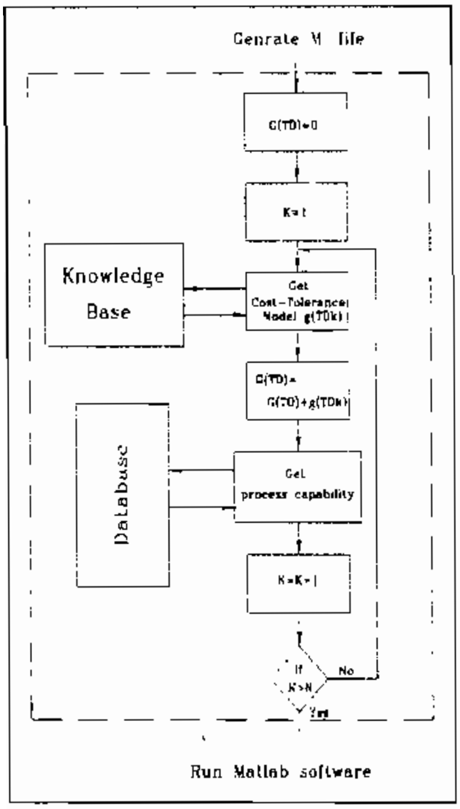

Figure 4 Algorithm for translate DXF file into TDF file

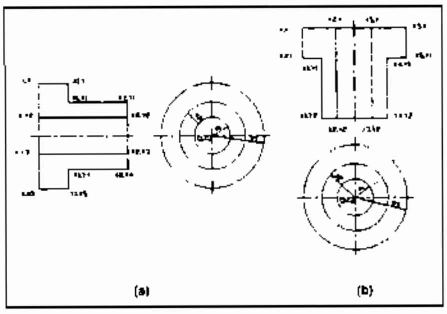

Figure 5. An example for part definition

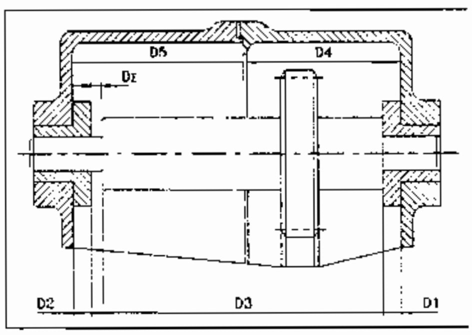

Figure 6. Mechanical assembly

7.1.2 Computer Model Procedure

The case study example is drawn using AutoCAD software, the drawing is saved as DXF file. When running the program the user selects option "Load DXF file" from the main menu, the program will ask the DXF file name. The system analyzes the file and detects individual parts of the assembly There are two cases :

The first case, the part has a defination in the program database then the program will recognize the part and the only input is the scaling factor (Ai) as shown in Fig. 7.

The second case when the part has not got a definition in the database then a menu will appear on the screen has the different forms of shapes and the user enters the form number as shown in Fig. 8, after that the user must input the nominal dimension and the scaling factor.

Finally the user inputs the function dimension, and can select on of two ways for solution.

The first solution is "Initial Tolerance Distribution" which produces an initial distribution for tolerances. This option may be used when the user needs a rough tolerance distribution (Fig. 9).

The second choice is "Optimum Tolerance Distribution" which is used to generate M-file for MATLAB software to produce optimum tolerance distribution as shown in Fig. 10.

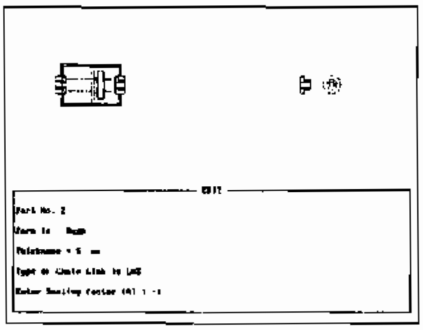

Figure 7.

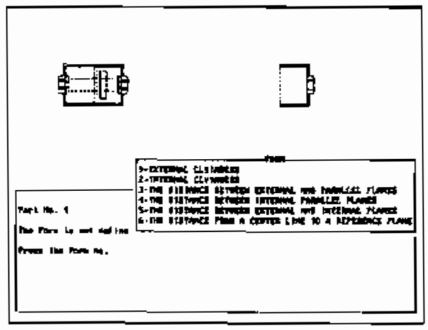

Figure 8.

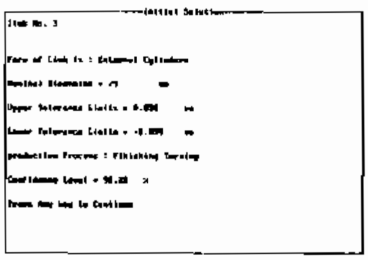

Figure 9.

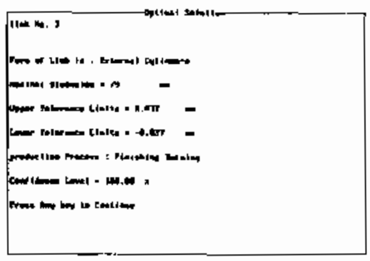

Figure 10.

8. Conclusion

This work introduces a method for tolerance distribution to individual parts in mechanical assemblies to satisfy the function requirments with minimum production cost. The new work ties between two different existing methods which are, tolerance .analysis and synthesis of tolerancing, and the second one is cost-tolerance algorithms. The integration between two methods have many advantage which are :

- There are a conection between tolerance distribution and confidence level of function dimension which means, it is possible to select a value for confidence level of the function dimension therefor the values of tolerance assignment will be changed due to this change.

-There is a guarantee to get the required tolerance at the desired position.

-Saving in production cost (is about 20% in the illustrated example).

This work introduces a computer system (CATD) to computerize the previous methods. The new system has the ability to be integrated with CAD systems. That means, it is possible to transfer data between CAD system to the new system without any human assistance by using rules of a form definitions in its knowledge base.

9. REFERENCES

[1] Bjorke, O., "Computer aided tolerancing", 2 nd edition, New York, ASME Press, 1989.

[2] Greenwood, W.H. and Chase, K.W., "A new tolerance analysis method for designer and manufacturer", J. of Eng. for Industry, Trans. of ASME, Vol. 109, P. 112-116, 1987.

[3] Balling, R.J., Free, J.C. and Parkinson, A.R., "Consideration of worst-case manufacturing tolerances in design optimization", J. of mechanisms, Transmission and Automation design, Trans., of ASME, Vol. 108, P 438-441, 1986.

[4] Dong, Z., and Soom, A., "Optimal tolerance design with automatic incorporation of manufacturing knowledge", IEE Integrated Systems Conference, 1989.

[5] Spotts M.F., "Dimensioning and tolerancing for quantity production", Published by Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1983.

[6] He J.R., "Tolerancing for manufacturing via cost minimization", Int. J. Mech. Tools Manufact., Vol. 31 No. 4, P 455-470, 1991.

[7] Trucks, H.E., "Designing for economical production", Society of Manufacuturing Engineers, FDearbon, Michigan, 1976.

[8] Dieter, G.E., "Engineering design a material and processing approach", McGraw-Hill, New York, 1983

[9] Speckhart, F.H., "Calculation of tolerance based on a minimum cost approach", J. of Engineering for Industry, Trans. of ASME, P 447-453, 1972.

[10] Spotts M.F., "Allocation tolerances to minimize cost of assembly", J. of Engineering for Industry, Trans. of ASME, P 762-764, 1973.

[11] Sutherland, G.H., Roth, B., "Mechanism esign: accounting for manufacturing tolerances and costs in function generalation problems", J. Eng. Ind., Trans. of ASME, Vol. 98, P. 283-286, 1975.

[12] Michel, W., and Siddal, J.N., "The optimization problem with optimal tolerance assignment and full acceptance", J. of Mechanical Design, Trans. of ASME, Vol. 103, P. 842-845, 1981.

[13] Chase, K.W., Greenwood, W.H., "Design issues in mechanical tolerance analysis", ASME Manuf. Rev., Vol. 1 No. 1, P. 50-59, 1988.

[14] Lee ,W.D. and Woo, T.C., "Optimum selection of discrete tolerances", J. of Mechanisms Transmission, and automation in design, Trans. of ASME, Vol. 111, P243-251, 1989.

[15] Wu., Z., Elmaraghy, W.H. and Elmaraghy, H.A., "Evaluation of cost-tolerance algorithms for design tolerane analysis synthesis", ASME Manu Rev., Vol. 1 No. 3, P 168-179, 1988.

[16] Dong, Z., Ho, W., and Dixue, D., "New production cost tolerance models for tolerance synthesis", J. of Engineering for industry, Vol. 116, P. 199-206, 1994.

[17] Karal, Anderou, "Computer aided tolerance analysis", Soe. Manufu. Eng., MS84, 762,P 1-14, 1984.

[18] I.M. Elewa and K.A. Kamal, "Computer-aided tolerance distribution for parts in mechanical assembly", First Engineering Conference, Mansoura, MP 254-256, 1995.