

---

# Figures

Figure P-1	Product development process .....	xxiv
Figure 1-1	Taguchi's loss function and a normal distribution .....	1-5
Figure 1-2	Graphical definition of short-term performance for a single characteristic .....	1-7
Figure 1-3	Graphical definition of long-term Six Sigma performance for a single characteristic (distribution shifted $1.5\sigma$ ) .....	1-8
Figure 2-1	Dimensional management tools .....	2-3
Figure 2-2	Variation simulation analysis .....	2-8
Figure 2-3	The dimensional management process .....	2-9
Figure 3-1	Linear dimensioning and tolerancing boundary example .....	3-3
Figure 3-2	Linear and geometric dimensioning and tolerancing boundary example .....	3-4
Figure 3-3	Fully geometric dimensioned and toleranced boundary example .....	3-6
Figure 3-4	Tolerance stack-up graph (linear tolerancing) .....	3-7
Figure 3-5	Plus/minus versus diametral tolerance zone comparison .....	3-9
Figure 3-6	Tolerance stack-up graph (position at RFS) .....	3-10
Figure 3-7	Tolerance stack-up graph (position at MMC) .....	3-12
Figure 3-8	Tolerance stack-up graph (zero position at MMC) .....	3-14
Figure 3-9	Summary graph .....	3-15
Figure 4-1	Note drawing .....	4-3
Figure 4-2	Casting drawing .....	4-5
Figure 4-3	Machined part made from casting .....	4-6
Figure 4-4	Machined part made from bar stock .....	4-7
Figure 4-5	Stamped sheet metal part drawing .....	4-8
Figure 4-6	Flat pattern layout drawing .....	4-9
Figure 4-7	Exploded pictorial assembly drawing .....	4-10
Figure 4-8	2-D sectioned assembly drawing .....	4-11
Figure 4-9	Border, title block, and revision block .....	4-12
Figure 4-10	First-angle projection .....	4-17
Figure 4-11	Third-angle projection .....	4-18
Figure 4-12	Auxiliary view development and arrangement .....	4-19
Figure 4-13	Full section .....	4-20
Figure 4-14	Half section .....	4-20
Figure 4-15	Offset section .....	4-21
Figure 4-16	Broken-out section .....	4-21
Figure 4-17	Revolved and removed section .....	4-22
Figure 4-18	Conventional breaks .....	4-22
Figure 4-19	Partial views .....	4-23
Figure 4-20	Internal and external feature rotation .....	4-24
Figure 4-21	Isometric projection .....	4-24
Figure 4-22	Envelope principle .....	4-26
Figure 4-23	General dimension types .....	4-26
Figure 4-24	Dimension elements and measurements .....	4-27
Figure 4-25	Surface characteristics .....	4-28
Figure 4-26	Surface texture examples and attributes .....	4-29
Figure 5-1	Drawing showing distance to ideal hole location .....	5-4
Figure 5-2	House built without all of the appropriate tools .....	5-5

**F-2 Figures**

Figure 5-3 House built using the correct tools ..... 5-5

Figure 5-4 Drawing that does not use GD&T ..... 5-6

Figure 5-5 Manufactured part that conforms to the drawing without GD&T (Fig. 5-4) ..... 5-7

Figure 5-6 Drawing that uses GD&T ..... 5-7

Figure 5-7 Using English to control part features ..... 5-12

Figure 5-8 Symbols used in dimensioning and tolerancing ..... 5-13

Figure 5-9 Compartments that make up the feature control frame ..... 5-14

Figure 5-10 Methods of attaching feature control frames ..... 5-17

Figure 5-11 Method of identifying a basic .875 dimension ..... 5-18

Figure 5-12 "Statistical tolerance" symbol ..... 5-18

Figure 5-13 Generating a size limit boundary ..... 5-21

Figure 5-14 Conformance to limits of size for a cylindrical feature ..... 5-21

Figure 5-15 Conformance to limits of size for a width-type feature ..... 5-22

Figure 5-16 Size limit boundaries control circularity at each cross section ..... 5-22

Figure 5-17 Levels of control for geometric tolerances modified to MMC ..... 5-24

Figure 5-18 Levels of control for geometric tolerances modified to LMC ..... 5-25

Figure 5-19 Cylindrical features of size that must fit in assembly ..... 5-26

Figure 5-20 Level 1's size limit boundaries will not assure assemblability ..... 5-26

Figure 5-21 Rule #1 specifies a boundary of perfect form at MMC ..... 5-27

Figure 5-22 Rule #1 assures matability ..... 5-28

Figure 5-23 Using an LMC modifier to assure adequate part material ..... 5-28

Figure 5-24 Feature of size associated with an MMC modifier and an LMC modifier ..... 5-29

Figure 5-25 Nullifying Rule #1 by adding a note ..... 5-29

Figure 5-26 MMC virtual condition of a cylindrical feature ..... 5-30

Figure 5-27 MMC virtual condition of a width-type feature ..... 5-31

Figure 5-28 LMC virtual condition of a cylindrical feature ..... 5-32

Figure 5-29 Using virtual condition boundaries to restrain orientation between mating features ..... 5-33

Figure 5-30 Using virtual condition boundaries to restrain location (and orientation) between mating features ..... 5-34

Figure 5-31 Zero orientation tolerance at MMC and zero positional tolerance at MMC ..... 5-36

Figure 5-32 Resultant condition boundary for the  $\varnothing.514$  hole in Fig. 5-30 ..... 5-37

Figure 5-33 Levels of control for geometric tolerances applied RFS ..... 5-39

Figure 5-34 Tolerance zone for straightness control RFS ..... 5-40

Figure 5-35 Tolerance zone for flatness control RFS ..... 5-40

Figure 5-36 Example of restrained and unrestrained actual mating envelopes ..... 5-41

Figure 5-37 The true geometric counterpart of datum feature B is a restrained actual mating envelope ..... 5-42

Figure 5-38 Actual mating envelope of an imperfect hole ..... 5-44

Figure 5-39 Actual minimum material envelope of an imperfect hole ..... 5-45

Figure 5-40 Straightness tolerance for line elements of a planar feature ..... 5-51

Figure 5-41 Flatness tolerance for a single planar feature ..... 5-52

Figure 5-42 Circularity tolerance (for nonspherical features) ..... 5-53

Figure 5-43 Circularity tolerance applied to a spherical feature ..... 5-54

Figure 5-44 Cylindricity tolerance ..... 5-55

Figure 5-45 Circularity tolerance with average diameter ..... 5-56

Figure 5-46 Cylindricity tolerance applied over a limited length ..... 5-57

Figure 5-47 Straightness tolerance applied on a unit basis ..... 5-57

Figure 5-48 Flatness tolerance applied on a unit basis ..... 5-58

Figure 5-49 Radius tolerance zone (where no center is drawn) ..... 5-58

Figure 5-50 Radius tolerance zone where a center is drawn ..... 5-59

Figure 5-51 Controlled radius tolerance zone ..... 5-60

Figure 5-52 Establishing datum reference frames from part features ..... 5-62

Figure 5-53 Selection of datum features ..... 5-63

Figure 5-54 Establishing datums on an engine cylinder head ..... 5-63

Figure 5-55 Selecting nonfunctional datum features ..... 5-64

Figure 5-56 Datum feature symbol ..... 5-65

Figure 5-57 Methods of applying datum feature symbols ..... 5-66

Figure 5-58 Parts contacting at high points ..... 5-67

Figure 5-59 Building a simple DRF from a single datum ..... 5-70

Figure 5-60 3-D Cartesian coordinate system ..... 5-70

Figure 5-61	Datum precedence for a cover mounted onto a base .....	5-71
Figure 5-62	Arresting six degrees of freedom between the cover and the TGC system .....	5-72
Figure 5-63	Comparison of datum precedence .....	5-74
Figure 5-64	Feature of size referenced as a primary datum RFS .....	5-76
Figure 5-65	Feature of size referenced as a secondary datum RFS .....	5-76
Figure 5-66	Feature of size referenced as a primary datum at MMC .....	5-77
Figure 5-67	Feature of size referenced as a secondary datum at MMC .....	5-77
Figure 5-68	Feature of size referenced as a primary datum at LMC .....	5-78
Figure 5-69	Feature of size referenced as a secondary datum at LMC .....	5-78
Figure 5-70	Bounded feature referenced as a primary datum at MMC .....	5-79
Figure 5-71	Bounded feature referenced as a secondary datum at MMC .....	5-79
Figure 5-72	Cylindrical feature of size, with straightness tolerance at MMC, referenced as a primary datum at MMC .....	5-80
Figure 5-73	Two possible locations and orientations resulting from datum reference frame (DRF) displacement .....	5-81
Figure 5-74	DRF displacement relative to a boundary of perfect form TGC .....	5-82
Figure 5-75	DRF displacement allowed by all the datums of the DRF .....	5-84
Figure 5-76	Unequal X and Y DRF displacement allowed by datum feature form variation .....	5-85
Figure 5-77	Unequal X and Y DRF displacement allowed by datum feature location variation .....	5-85
Figure 5-78	“Common DRF” means “identical DRF” .....	5-86
Figure 5-79	Using simultaneous requirements rule to tie together the boundaries of five features .....	5-87
Figure 5-80	Specifying separate requirements .....	5-88
Figure 5-81	Imposing simultaneous requirements by adding a note .....	5-88
Figure 5-82	Datum feature surface that does not have a unique three-point contact .....	5-89
Figure 5-83	Acceptable and unacceptable contact between datum feature and datum feature simulator .....	5-90
Figure 5-84	Datum target identification .....	5-93
Figure 5-85	Datum target application on a rectangular part .....	5-94
Figure 5-86	Datum target application on a cylindrical part .....	5-96
Figure 5-87	Using datum targets to establish a primary axis from a revolute .....	5-98
Figure 5-88	Setup for simulating the datum axis for Fig. 5-87 .....	5-99
Figure 5-89	Target set with switchable datum precedence .....	5-100
Figure 5-90	Three options for establishing the origin from a pattern of dowel holes .....	5-101
Figure 5-91	Pattern of holes referenced as a single datum at MMC .....	5-102
Figure 5-92	Application of orientation tolerances .....	5-104
Figure 5-93	Tolerance zones for Fig. 5-92 .....	5-105
Figure 5-94	Application of tangent plane control .....	5-105
Figure 5-95	Applying an angularity tolerance to a width-type feature .....	5-106
Figure 5-96	Applying an angularity tolerance to a cylindrical feature .....	5-107
Figure 5-97	Controlling orientation of line elements of a surface .....	5-108
Figure 5-98	Applications of orientation tolerances .....	5-110
Figure 5-98	Applications of orientation tolerances (continued) .....	5-111
Figure 5-99	Erroneous wedge-shaped tolerance zone .....	5-112
Figure 5-100	Controlling the location of a feature with a plus and minus tolerance .....	5-113
Figure 5-101	Methods for establishing true positions .....	5-114
Figure 5-102	Alternative methods for establishing true positions using polar coordinate dimensioning .....	5-115
Figure 5-103	Restraining four degrees of freedom .....	5-116
Figure 5-104	Implied datums are not allowed .....	5-117
Figure 5-105	Establishing true positions for angled features—one correct method .....	5-118
Figure 5-106	Establishing true positions from an implied datum—a common error .....	5-118
Figure 5-107	Specifying a projected tolerance zone .....	5-119
Figure 5-108	Showing extent and direction of projected tolerance zone .....	5-119
Figure 5-109	Projected tolerance zone at MMC .....	5-120
Figure 5-110	Different positional tolerances (RFS) at opposite extremities .....	5-121
Figure 5-111	Bidirectional positional tolerancing, rectangular coordinate system .....	5-122
Figure 5-112	Virtual condition boundaries for bidirectional positional tolerancing at MMC, rectangular coordinate system .....	5-123
Figure 5-113	Tolerance zone for bidirectional positional tolerancing applied RFS, rectangular coordinate system .....	5-124
Figure 5-114	Bidirectional positional tolerancing, polar coordinate system .....	5-125
Figure 5-115	Positional tolerancing of a bounded feature .....	5-126

## F-4 Figures

Figure 5-116	Standard catalog handle .....	5-127
Figure 5-117	Handle technical bulletin .....	5-128
Figure 5-118	Avionics “black box” with single positional tolerance on pattern of holes .....	5-128
Figure 5-119	Avionics “black box” with composite positional tolerance on pattern of holes .....	5-129
Figure 5-120	PLTZF virtual condition boundaries for Fig. 5-119 .....	5-130
Figure 5-121	FRTZF virtual condition boundaries for Fig. 5-119 .....	5-131
Figure 5-122	One possible relationship between the PLTZF and FRTZF for Fig. 5-119 .....	5-132
Figure 5-123	One possible relationship between the PLTZF and FRTZF with datum B referenced in the lower segment .....	5-133
Figure 5-124	Two stacked single-segment feature control frames .....	5-134
Figure 5-125	Virtual condition boundaries of the upper frame for Fig. 5-124 .....	5-135
Figure 5-126	Virtual condition boundaries of the lower frame for Fig. 5-124 .....	5-135
Figure 5-127	Three-segment composite feature control frame .....	5-137
Figure 5-128	Design applications for runout control .....	5-138
Figure 5-129	Symbols for circular runout and total runout .....	5-139
Figure 5-130	Datums for runout control .....	5-140
Figure 5-131	Two coaxial features establishing a datum axis for runout control .....	5-141
Figure 5-132	Runout control of hyphenated co-datum features .....	5-142
Figure 5-133	Application of circular runout .....	5-143
Figure 5-134	Application of profile tolerances .....	5-146
Figure 5-135	Profile tolerance zones .....	5-148
Figure 5-136	Profile of a line tolerance .....	5-150
Figure 5-137	Profile “all around” .....	5-151
Figure 5-138	Profile “all over” .....	5-151
Figure 5-139	Profile “between” points .....	5-152
Figure 5-140	Profile tolerancing to control a combination of characteristics .....	5-153
Figure 5-141	Profile tolerance to control coplanarity of three feet .....	5-154
Figure 5-142	Composite profile for a pattern .....	5-155
Figure 5-143	Composite profile tolerancing with separate Level 2 control .....	5-155
Figure 5-144	Composite profile tolerance for a single feature .....	5-156
Figure 5-145	Types of symmetry .....	5-157
Figure 5-146	Symmetry construction rays .....	5-158
Figure 5-147	Symmetry tolerance about a datum plane .....	5-159
Figure 5-148	Multifold concentricity tolerance on a cam .....	5-160
Figure 5-149	Dimension origin symbol .....	5-163
Figure 7-1	Vectors and unit vectors .....	7-5
Figure 7-2	Vector addition .....	7-5
Figure 7-3	Vector subtraction .....	7-6
Figure 7-4	Circularity tolerance zone definition .....	7-10
Figure 7-5	Illustration of an elliptical cylinder .....	7-11
Figure 7-6	Cylindricity tolerance definition .....	7-12
Figure 7-7	Flatness tolerance definition .....	7-13
Figure 8-1	Statistical tolerancing using process capability indices .....	8-3
Figure 8-2	Statistical tolerancing using RMS deviation index .....	8-4
Figure 8-3	Statistical tolerancing using percent containment .....	8-5
Figure 8-4	Population parameter zones for the specifications in Fig. 8.1 .....	8-6
Figure 8-5	Population parameter zones for the specifications in Fig. 8.2 .....	8-6
Figure 8-6	Population parameter zones for the specifications in Fig. 8.3 .....	8-7
Figure 8-7	Additional illustration of specifying percent containment .....	8-7
Figure 8-8	Illustration specifying process capability indices .....	8-8
Figure 8-9	Additional illustration specifying process capability indices .....	8-8
Figure 8-10	Illustration of statistical tolerancing under MMC .....	8-9
Figure 9-1	Tolerance analysis process .....	9-2
Figure 9-2	Motor assembly .....	9-3
Figure 9-3	Horizontal loop diagram for Requirement 6 .....	9-4
Figure 9-4	Methods to dimension the length of a shaft .....	9-5
Figure 9-5	Methods of centering manufacturing processes .....	9-6
Figure 9-6	Combining piecepart variations using worst case and statistical methods .....	9-8
Figure 9-7	Graph of piecepart tolerances versus assembly tolerance before and after resizing using the Worst Case Model .....	9-11

Figure 9-8	Graph of piecepart tolerances versus assembly tolerance before and after resizing using the RSS Model .....	9-16
Figure 9-9	Graph of piecepart tolerances versus assembly tolerance before and after resizing using the MRSS Model .....	9-20
Figure 9-10	Substrate package .....	9-26
Figure 9-11	Position at RFS .....	9-27
Figure 9-12	Position at MMC — internal feature .....	9-29
Figure 9-13	Position at MMC — external feature .....	9-30
Figure 9-14	Position at LMC — internal feature .....	9-31
Figure 9-15	Position at LMC — external feature .....	9-31
Figure 9-16	Composite position and composite profile .....	9-32
Figure 9-17	Circular and total runout .....	9-33
Figure 9-18	Concentricity .....	9-33
Figure 9-19	Equal bilateral tolerance profile .....	9-34
Figure 9-20	Unilateral tolerance profile .....	9-35
Figure 9-21	Unequal bilateral tolerance profile .....	9-35
Figure 9-22	Size datum .....	9-36
Figure 10-1	Histogram of runout (FIM) data .....	10-2
Figure 10-2	The normal distribution .....	10-3
Figure 10-3	Histogram of normal, n=5, with normal curve .....	10-4
Figure 10-4	Histogram of normal, n=50, with normal curve .....	10-4
Figure 10-5	Histogram of normal, n=500, with normal curve .....	10-5
Figure 10-6	Histogram of normal, n=5000, with normal curve .....	10-5
Figure 10-7	Z Statistic .....	10-6
Figure 10-8	Normality test FIM .....	10-7
Figure 10-9	Histogram of transformed FIM measurements .....	10-7
Figure 10-10	Normality tests for transformed data .....	10-8
Figure 10-11	Attributes data .....	10-8
Figure 10-12	Plot of Poisson probabilities .....	10-10
Figure 10-13	Process capability .....	10-11
Figure 10-14	Capability index .....	10-11
Figure 10-15	Capability index at ± 4 sigma .....	10-11
Figure 10-16	The reality .....	10-12
Figure 10-17	Cp and Cpk at Six Sigma .....	10-13
Figure 10-18	Yields through multiple CTQs .....	10-13
Figure 11-1	Comparison of tolerance analysis and tolerance allocation .....	11-2
Figure 11-2	Motor assembly .....	11-5
Figure 11-3	Worst case allocation flow chart .....	11-6
Figure 11-4	Dimension loop for Requirement 6 .....	11-7
Figure 11-5	Effect of shifting the mean of a normal distribution to the right .....	11-11
Figure 11-6	Centered normal distribution. Both tails are significant. ....	11-12
Figure 11-7	Statistical allocation flow chart .....	11-14
Figure 11-8	Normal distribution that has been truncated due to inspection .....	11-17
Figure 11-9	Three options for designating a statistically derived tolerance on an engineering drawing .....	11-25
Figure 12-1	Geneva mechanism showing a few of the relevant dimensions .....	12-2
Figure 12-2	Linearized approximation to a curve .....	12-3
Figure 12-3	Multidimensional tolerancing flow chart .....	12-4
Figure 12-4	Stacked blocks we will use for an example problem .....	12-5
Figure 12-5	Gap coordinate system $\{\mathbf{u}_1, \mathbf{u}_2\}$ .....	12-6
Figure 12-6	Possible vector loops to evaluate the gap of interest .....	12-6
Figure 12-7	Vector loop we will use to analyze the gap. It presents easier calculations of unknown vector lengths. ....	12-7
Figure 12-8	Additional coordinate system needed for the vectors on Block 2 .....	12-7
Figure 12-9	Relationship between coordinate systems $\{\mathbf{u}_1, \mathbf{u}_2\}$ and $\{\mathbf{v}_1, \mathbf{v}_2\}$ .....	12-9
Figure 13-1	Kinematic adjustment due to component dimension variations .....	13-2
Figure 13-2	Adjustment due to geometric shape variations .....	13-2
Figure 13-3	Stacked blocks assembly .....	13-3
Figure 13-4	Assembly graph of the stacked blocks assembly .....	13-4
Figure 13-5	2-D kinematic joint and datum types .....	13-4
Figure 13-6	Part datums and assembly variables .....	13-5

## F-6 Figures

Figure 13-7	Datum paths for Joints 1 and 2 .....	13-6
Figure 13-8	Datum paths for Joints 3 and 4 .....	13-6
Figure 13-9	2-D vector path through the joint contact point .....	13-7
Figure 13-10	2-D vector path across a part .....	13-8
Figure 13-11	Assembly Loop 1 .....	13-9
Figure 13-12	Assembly Loop 2 .....	13-9
Figure 13-13	Propagation of 2-D translational and rotational variation due to surface waviness .....	13-10
Figure 13-14	Applied geometric variations at contact points .....	13-11
Figure 13-15	Assembly tolerance controls .....	13-12
Figure 13-16	Open loop describing critical assembly gap .....	13-13
Figure 13-17	Relative rotations for Loop 1 .....	13-14
Figure 13-18	Percent contribution chart for the sample assembly .....	13-22
Figure 13-19	Percent contribution chart for the sample assembly with modified tolerances .....	13-23
Figure 13-20	Modified geometry yields zero $\theta$ contribution .....	13-26
Figure 13-21	The CATS System .....	13-27
Figure 14-1	Optimal tolerance allocation for minimum cost .....	14-2
Figure 14-2	Graphical interpretation of minimum cost tolerance allocation .....	14-4
Figure 14-3	Shaft and housing assembly .....	14-4
Figure 14-4	Tolerance range of machining processes (Reference 12) .....	14-5
Figure 14-5	Comparison of minimum cost allocation results .....	14-7
Figure 14-6	Clutch assembly with vector loop .....	14-9
Figure 14-7	Tolerance allocation results for a Worst Case Model .....	14-13
Figure 14-8	Tolerance allocation results for the RSS Model .....	14-14
Figure 14-9	Tolerance allocation results for the modified RSS Model .....	14-15
Figure 14-10	Tolerance allocation results for the modified WC Model .....	14-16
Figure 14-11	Tolerance allocation results for the WC Model .....	14-16
Figure 14-12	Tolerance allocation results for the RSS Model .....	14-17
Figure 14A-1	Plot of cost versus tolerance for fitted and raw data for the turning process .....	14-18
Figure 14A-2	Plot of fitted cost versus tolerance functions .....	14-21
Figure 14A-3	Plot of coefficients versus size for cost-tolerance functions .....	14-22
Figure 14A-3	Plot of coefficients versus size for cost-tolerance functions (continued) .....	14-23
Figure 15-1	Tolerancing process .....	15-3
Figure 15-2	Small kinematic adjustments .....	15-4
Figure 15-3	Communication between design and manufacturing .....	15-9
Figure 16-1	Information flow in the product development process .....	16-2
Figure 16-2	Master model process information .....	16-5
Figure 16-3	Data management hierarchy .....	16-12
Figure 16-4	File format for one triangle in an STL file .....	16-21
Figure 17-1	Narrow road versus three-lane road .....	17-5
Figure 17-2	Data collected from a process with a shifted target .....	17-5
Figure 17-3	Averaging and grouping short-term data .....	17-6
Figure 17-4	Feature factoring methodology flexibility .....	17-7
Figure 17-5	Dpmo-weighting and guard-banding technique .....	17-8
Figure 18-1	Directional indicators for data point plotting .....	18-4
Figure 18-2	Example four-hole part .....	18-5
Figure 18-3	Layout inspection of four-hole part .....	18-6
Figure 18-4	Plotting the holes on the coordinate grid .....	18-7
Figure 18-5	Overlaying the polar coordinate system .....	18-7
Figure 18-6	Example four-hole part with long holes .....	18-8
Figure 18-7	Plotting 3-dimensional hole data on the coordinate grid .....	18-9
Figure 18-8	Four-hole part controlled by composite positional tolerancing .....	18-10
Figure 18-9	Paper gage verification of hole pattern location .....	18-11
Figure 18-10	Paper gage verification of feature-to-feature location .....	18-11
Figure 18-11	Datum feature subject to size variation — RFS applied .....	18-12
Figure 18-12	Paper gage verification for datum applied at MMC .....	18-13
Figure 18-13	Layout inspection setup of workpiece .....	18-14
Figure 18-14	Inspection Report — part allowing datum shift .....	18-14
Figure 18-15	Verifying hole pattern prior to datum shift .....	18-15
Figure 18-16	Verifying the hole pattern after datum shift .....	18-16
Figure 18-17	Part allowing rotational datum shift .....	18-16

Figure 18-18	Inspection Report — part allowing rotational datum shift .....	18-17
Figure 18-19	Verifying hole pattern prior to rotational shift.....	18-18
Figure 18-20	Verifying hole pattern after rotational datum shift.....	18-18
Figure 18-21	Example of datum established from a hole pattern .....	18-19
Figure 18-22	Inspection Report — hole pattern as a datum.....	18-20
Figure 18-23	Determining the central datum axis from a hole pattern .....	18-20
Figure 18-24	Approximating datum shift from a hole pattern .....	18-21
Figure 18-25	Process evaluation using a paper gage .....	18-22
Figure 19-1	Position using partial and planar datum features .....	19-4
Figure 19-2	Gage for verifying two-hole pattern in Fig. 19-1 .....	19-6
Figure 19-3	Position using datum features of size at MMC .....	19-7
Figure 19-4	Gage for verifying four-hole pattern in Fig. 19-3 .....	19-8
Figure 19-5	Position and profile using a simultaneous gaging requirement .....	19-9
Figure 19-6	Gage for simulating datum features in Fig. 19-5 .....	19-10
Figure 19-7	Gage for verifying four-hole pattern and profile outer boundary in Fig. 19-5 .....	19-11
Figure 19-8	Position using centerplane datums .....	19-12
Figure 19-9	Gage for verifying four-hole pattern in Fig. 19-8 .....	19-13
Figure 19-10	Multiple datum structures .....	19-14
Figure 19-11	Gage for verifying datum feature D in Fig. 19-10 .....	19-15
Figure 19-12	Gage for verifying four-hole pattern in Fig. 19-10 .....	19-16
Figure 19-13	Secondary and tertiary datum features of size.....	19-17
Figure 19-14	Gage for verifying datum features D and E in Fig. 19-13 .....	19-18
Figure 19-15	Gage for verifying five holes in Fig. 19-13 .....	19-19
Figure 20-1	Z-Axis single-point repeatability .....	20-21
Figure 20-2a	Form Six Sigma versus probe settling time (10-mm sphere) .....	20-22
Figure 20-2b	Sphere form versus probe settling time (25-mm sphere) .....	20-22
Figure 20-3	Probe speed versus sphere form.....	20-23
Figure 20-4	Sphere form versus probe trigger force (10-mm sphere) .....	20-24
Figure 20-5	Circle features versus probe deflection .....	20-25
Figure 20-6	Cylinder features versus probe deflection .....	20-26
Figure 20-7	Probe deflection versus sphere form.....	20-27
Figure 20-8	Circle features versus hole diameter .....	20-29
Figure 20-9	Cylinder features versus hole diameter .....	20-29
Figure 20-10a	Bidirectional probing versus varying lengths (x-axis) .....	20-30
Figure 20-10b	Bidirectional probing versus varying lengths (y-axis) .....	20-31
Figure 20-11	Circle features versus number of points per section .....	20-31
Figure 20-12	Cylinder features versus number of points/section .....	20-32
Figure 20-13	Cylinder features versus number points/section .....	20-33
Figure 20-14	Cylinder features versus number of points/section .....	20-33
Figure 20-15	25-mm cube test — single versus star probe setup .....	20-34
Figure 20-16	Circle features versus scanning speed .....	20-35
Figure 20-17	Leitz PPM 654 capability matrix .....	20-36
Figure 20-17	Leitz PPM 654 capability matrix (continued) .....	20-37
Figure 21-1	Cylindrical (size) feature with orientation and location constraints at RFS .....	21-3
Figure 21-2	Allowable location tolerance as a function of orientation error ( $\theta$ ) .....	21-4
Figure 21-3	Cylindrical (size) feature with orientation and location constraints at MMC .....	21-6
Figure 21-4	Cylindrical (size) feature with orientation and location constraints at LMC .....	21-7
Figure 21-5	Parallel plane (size) feature with orientation and location constraints at RFS .....	21-9
Figure 22-1	Examples of floating fasteners .....	22-2
Figure 22-2	Examples of fixed fasteners .....	22-3
Figure 22-3	Examples of double-fixed fasteners .....	22-4
Figure 22-4	Rectangular tolerance zone (plus/minus tolerancing) .....	22-5
Figure 22-5	Cylindrical tolerance zone .....	22-5
Figure 22-6	Tapped hole located (.000, .000) and clearance hole off location by (+.005, .000) .....	22-6
Figure 22-7	Tapped hole is located (-.005, .000) and clearance hole is located (+.005, .000) .....	22-6
Figure 22-8	Tapped hole is located (-.005, -.005) and clearance hole is located (+.005, +.005) .....	22-7
Figure 22-9	Tapped hole is located (-.007, .000) and clearance hole is located (+.007, .000) .....	22-7
Figure 22-10	Additional tolerance allowed by using a cylindrical tolerance zone versus a rectangular tolerance zone .....	22-8
Figure 22-11	Worst case head height above the surface .....	22-12

**F-8 Figures**

Figure 22-12 Worst case head height below the surface ..... 22-12

Figure 22-13 Flat head fastener dimensions for a .250-28-UNC 2B flat head fastener ..... 22-13

Figure 22-14 Positional tolerance for clearance holes and nut plate rivet holes ..... 22-15

Figure 22-15 Tapped hole out of perpendicular by  $\varnothing.014$  ..... 22-15

Figure 22-16 Variation in perpendicularity could cause assembly problems ..... 22-15

Figure 22-17 Projected tolerance zone example ..... 22-16

Figure 22-18 Projected tolerance zone — location and orientation components ..... 22-17

Figure 22-19 Lost functional tolerance versus actual orientation tolerance ..... 22-18

Figure 22-20 Floating fastener tolerance and callouts ..... 22-20

Figure 22-21 Fixed fastener tolerance and callouts ..... 22-21

Figure 22-22 Double-fixed fastener tolerance and callouts ..... 22-23

Figure 23-1 Feature located using positional tolerance at MMC ..... 23-2

Figure 23-2 Dimension loop diagram for Fig. 23-1 ..... 23-3

Figure 23-3 Fixed fastener centered and shifted ..... 23-4

Figure 23-4 Floating fastener centered and shifted ..... 23-4

Figure 23-5 Fixed fastener assembly ..... 23-5

Figure 23-6 Fixed fastener minimum assembly gap ..... 23-6

Figure 23-7 Fixed fastener maximum assembly gap ..... 23-6

Figure 23-8 Centered fixed fastener dimension loop diagram ..... 23-8

Figure 23-9 Floating fastener assembly ..... 23-8

Figure 24-1 Examples of design cases for alignment pins showing Type I and Type II errors ..... 24-4

Figure 24-2 Two common cross-sections for modified pins ..... 24-6

Figure 24-3 Design process for using alignment data ..... 24-8

Figure 24-4 Variables contributing to fit of two round pins with two holes ..... 24-12

Figure 24-5 Variables contributing to rotation caused by two round pins with two holes ..... 24-13

Figure 24-6 Dimensioning methodology for two round pins with two holes ..... 24-14

Figure 24-7 Variables contributing to fit of two round pins with one hole and one slot ..... 24-16

Figure 24-8 Variables contributing to rotation caused by two pins with one hole and one slot ..... 24-16

Figure 24-9 Dimensioning methodology for two round pins with one hole and one slot ..... 24-18

Figure 24-10 Variables contributing to rotation caused by two pins with hole and edge contact ..... 24-20

Figure 24-11 Dimensioning methodology for two round pins with one hole and edge contact ..... 24-21

Figure 24-12 Variables contributing to fit of one round pin and one diamond pin with two holes ..... 24-23

Figure 24-13 Variables contributing to the fit of one pin and one parallel-flats pin with two holes ..... 24-26

Figure 25-1 Sample drawing #1 ..... 25-2

Figure 25-2 Sample drawing #2 ..... 25-3

Figure 25-3 Sample drawing #3 ..... 25-3

Figure 25-4 Sample drawing #4 ..... 25-5



---

# Tables

Table 1-1	Practical impact of process capability .....	1-8
Table 3-1	Bonus tolerance gained as the feature's size is displaced from its MMC .....	3-13
Table 5-1	Geometric characteristics and their attributes .....	5-15
Table 5-2	Modifying symbols .....	5-16
Table 5-3	Actual mating envelope restraint .....	5-42
Table 5-4	Datum feature types and their TGCs .....	5-68
Table 5-5	TGC shape and the derived datum .....	5-69
Table 5-6	Datum target types .....	5-92
Table 5-7	Simultaneous/separate requirement defaults .....	5-133
Table 6-1	ASME standards that are related to dimensioning .....	6-2
Table 6-2	ISO standards that are related to dimensioning .....	6-3
Table 6-3	Organization of the matrix model from ISO technical report (#TR 14638) .....	6-4
Table 6-4	Differences between ASME and ISO standards .....	6-5
Table 6-5	Advantages and disadvantages of the number of ASME and ISO standards .....	6-6
Table 6-6A	General .....	6-7
Table 6-6B	General .....	6-8
Table 6-6C	General .....	6-9
Table 6-6D	General .....	6-10
Table 6-6E	General .....	6-11
Table 6-6F	General .....	6-12
Table 6-7A	Form .....	6-13
Table 6-7B	Form .....	6-14
Table 6-8A	Datums .....	6-15
Table 6-8B	Datums .....	6-16
Table 6-8C	Datums .....	6-17
Table 6-8D	Datums .....	6-18
Table 6-9	Orientation .....	6-19
Table 6-10A	Tolerance of Position .....	6-20
Table 6-10B	Tolerance of Position .....	6-21
Table 6-10C	Tolerance of Position .....	6-22
Table 6-10D	Tolerance of Position .....	6-23
Table 6-11	Symmetry .....	6-24
Table 6-12	Concentricity .....	6-25
Table 6-13A	Profile .....	6-25
Table 6-13B	Profile .....	6-26
Table 6-14	A sample of the national standards bodies that exist .....	6-27
Table 6-15	International standardizing organizations .....	6-28
Table 9-1	Converting to mean dimensions with equal bilateral tolerances .....	9-7
Table 9-2	Dimensions and tolerances used in Requirement 6 .....	9-7
Table 9-3	Resized tolerances using the Worst Case Model .....	9-11
Table 9-4	Resized tolerances using the RSS Model .....	9-17
Table 9-5	Resized tolerances using the MRSS Model .....	9-20
Table 9-6	Comparison of results using the Worst Case, RSS, and MRSS models .....	9-22
Table 9-7	Comparison of analysis models .....	9-23

**T-2 Tables**

Table 10-1	Distribution of defects .....	10-9
Table 11-1	Process standard deviations that will be used in this chapter .....	11-3
Table 11-2	Data used to allocate tolerances for Requirement 6 .....	11-7
Table 11-3	Final allocated and fixed tolerances to meet Requirement 6 .....	11-10
Table 11-4	Fixed and statistically allocated tolerances for Requirement 6 .....	11-18
Table 11-5	Fixed and statistically allocated tolerances for Requirement 6 .....	11-19
Table 11-6	Standard deviation inflation factors and DRSS allocated tolerances for Requirement 6 .....	11-22
Table 11-7	Comparison of the allocated tolerances for Requirement 6 .....	11-24
Table 12-1	Dimensions and tolerances corresponding to the variable names in Fig. 12-4 .....	12-5
Table 12-2	Dimensions, tolerances, and sensitivities for the stacked block assembly .....	12-12
Table 12-3	Final dimensions, tolerances, and sensitivities of the stacked block assembly .....	12-13
Table 13-1	Estimated variation in open and closed loop assembly features .....	13-21
Table 13-2	Modified dimensional tolerance specifications .....	13-23
Table 13-3	Calculated sensitivities for the Gap .....	13-24
Table 13-4	Calculated sensitivities for the Gap after modifying geometry .....	13-25
Table 13-5	Variation results for modified nominal geometry .....	13-25
Table 14-1	Proposed cost-of-tolerance models .....	14-2
Table 14-2	Initial Tolerance Specifications .....	14-5
Table 14-3	Minimum cost tolerance allocation .....	14-7
Table 14-4	Minimum True Cost .....	14-8
Table 14-5	Independent dimensions for the clutch assembly .....	14-9
Table 14-6	Process tolerance limits for the clutch assembly .....	14-11
Table 14-7	Expressions for minimum cost tolerances in 2-D and 3-D assemblies .....	14-12
Table 14-8	Process tolerance cost data for the clutch assembly .....	14-12
Table 14-9	Revised process tolerance cost data for the clutch assembly .....	14-15
Table 14A-1	Relative cost of obtaining various tolerance levels .....	14-19
Table 14A-2	Cost-tolerance functions for metal removal processes .....	14-20
Table 15-1	Advanced tolerance analysis methods: MSM versus MCS .....	15-8
Table 16-1	Information captured in a database .....	16-5
Table 16-2	Examples of templates .....	16-8
Table 16-3	Common document templates .....	16-9
Table 16-4	Information provided for sheetmetal process .....	16-16
Table 16-5	Information provided for injection molding process .....	16-17
Table 16-6	Information provided for hog-out process .....	16-17
Table 16-7	Information provided for casting process .....	16-18
Table 16-8	Information provided for prototyping process .....	16-19
Table 18-1	Layout Inspection Report of four-hole part .....	18-6
Table 18-2	Inspection Report for part with long holes .....	18-9
Table 18-3	Inspection Report for composite position verification .....	18-10
Table 22-1	Floating fastener clearance hole and C'Bore hole sizes and tolerances .....	22-19
Table 22-2	Fixed fastener clearance hole, C'Bore, and C'Sink sizes and tolerances .....	22-22
Table 22-3	Double-fixed fastener clearance hole and C'Bore sizes and tolerances .....	22-24
Table 22-4	C'Bore depths (pan head and socket head) .....	22-25
Table 22-5	Flat head screw head height above and below the surface .....	22-26
Table 24-1	Alignment pins per ANSI B18.8.2-1978, R1989 .....	24-5
Table 24-2	Standard deviations for common manufacturing processes (inches) .....	24-7
Table 24-3	Performance constants for two round pins with two holes .....	24-13
Table 24-4	GD&T callouts for two round pins with two holes .....	24-15
Table 24-5	Performance constants for two round pins with one hole and one slot .....	24-17
Table 24-6	GD&T callouts for two round pins with one hole and one slot .....	24-19
Table 24-7	Performance constants for two round pins with one hole and edge contact .....	24-21
Table 24-8	GD&T callouts for two round pins with one hole and edge contact .....	24-22
Table 24-9	Performance constants for one round pin and one diamond pin with two holes .....	24-24
Table 24-10	GD&T callouts for one round pin and one diamond pin with two holes .....	24-25
Table 24-11	Performance constants for one round pin and one parallel-flats pin with two holes .....	24-27
Table 24-12	GD&T callouts for one round pin with one parallel-flats pin and two holes .....	24-28
Table 25-1	GR&R Analysis Matrix .....	25-2
Table 25-2	Bonus tolerance gained due to considered feature size .....	25-5
Table 25-3	Analysis Matrix .....	25-6