



**ESDU 00015**

Issued May 2000  
With Amendment A  
May 2010

# **Disc cams: tribological analysis using computer program A0015**

**Associated software: ESDUpac A0015**

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## THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Bearing Dynamics Working Party:

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## DISC CAMS: TRIBOLOGICAL ANALYSIS USING COMPUTER PROGRAM A0015

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## DISC CAMS: TRIBOLOGICAL ANALYSIS USING COMPUTER PROGRAM A0015

### 1. INTRODUCTION

This Data Item describes the use of ESDUpac A0015 which provides a computer program for analysing a disc cam/follower system. The program allows the following tribological aspects to be examined.

- The surface and sub-surface stresses at the contact between the cam and follower.
- The lubricant film thickness generated between the cam and follower.
- The transient temperature rise ("flash" temperature) in the contact between the cam and follower.
- The driving torque and power loss of the cam.
- The life of a rolling element bearing follower.

The program determines the contact loads, with or without friction, in the operating cam/follower system and then determines the instantaneous contact dimensions, gross deflection (normal closure) and contact stresses. The program locates the critical stress points with respect to three criteria involving yield failure, brittle failure and fatigue failure.

Where a Newtonian liquid lubricant is present, the program can be used to predict the film thickness of the lubricant entrained into the contact. Computation of this lubricant film thickness includes an allowance for squeeze film effects at the points in the cam cycle where the entrainment velocity reverses.

Six types of cam follower are considered including both translating and swinging versions of flat-faced, domed, and roller followers. Also, follower motions involving any number of blended cam law portions can be analysed. The cam law of each portion can be selected from a supplied database of cam law expressions or can be specified by the user. The follower load, arising from spring closure or a process load, can similarly be selected from a database or be specified by the user.

Computer parameters of interest can be logged over a full, or partial, cycle of cam rotation and the values recorded in a file suitable for plotting. Alternatively, a single instantaneous point in the cycle can be examined in more detail and stress distribution contours, for example, examined.

This Data Item documents the specification of input data for the program and describes the various output data that can be obtained. Guidance on interpretation of the output data is given in further Data Items devoted to specific tribological aspects. Guidance on, and methods for, the design of cams can be found in the ESDU Mechanisms Series (see Section 11). ESDUpac A0015 allows the direct import of motion data from many of the Mechanisms Series computer programs (see Section 4.2).

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## 2. NOTATION AND UNITS

This Notation lists all of the symbols used and referred to in this Data Item. The International System of units is used. The symbols (parameter names) used in the input and output files for ESDUpac A0015 of necessity differ from those used in derivative Data Items (see Section 11). Only the symbols used in the program files are listed here.

| Symbol | Description                                                                                                                                                  | Units              |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|
| a      | major semi-axis of contact ellipse or rectangle (see Sketch 2.2)                                                                                             | m                  |
| alpha  | pressure angle defined as acute angle measured positive anticlockwise from follower line of action to contact normal (see Sketch 2.3)                        | degree             |
| alpT   | face angle for translating flat-faced follower (see Table 4.2)                                                                                               | degree             |
| alp0   | pressure exponent of lubricant viscosity (see Derivation 17)                                                                                                 | m <sup>2</sup> /N  |
| b      | minor semi-axis of contact ellipse or rectangle (see Sketch 2.2)                                                                                             | m                  |
| body   | body of interest specified as 'Cam' or 'Follower'                                                                                                            | —                  |
| C      | swinging follower arm crank length (see Table 4.2)                                                                                                           | m                  |
| cMu    | critical value of friction coefficient to just prevent follower roller slip                                                                                  | —                  |
| CxC    | cam crown curvature (assumed to be zero)                                                                                                                     | 1/m                |
| CxF    | follower crown curvature = 1/Rc                                                                                                                              | 1/m                |
| CyC    | cam profile curvature equal to reciprocal of profile radius                                                                                                  | 1/m                |
| CyF    | follower profile curvature (dome or roller) = 1/Rf                                                                                                           | 1/m                |
| D      | cam centre/follower pivot distance (see Table 4.2)                                                                                                           | m                  |
| delta  | normal approach of cam and follower defined as decrease in separation between two points on contact normal, one in each body, remote from compressed region. | m                  |
| disF   | name of stress distributions file                                                                                                                            | —                  |
| disS   | list of symbols of stresses for distributions                                                                                                                | —                  |
| dQo    | change in orthogonal shear stress for a given element of material as it passes under the contact (see Derivation 6)                                          | N/m <sup>2</sup>   |
| dQoMax | maximum change in orthogonal shear stress                                                                                                                    | N/m <sup>2</sup>   |
| Dwell  | signifies dwell portion in input file (see Section 4.2)                                                                                                      | —                  |
| E      | translating follower offset (see Table 4.2)                                                                                                                  | m                  |
| Ec     | elastic modulus of cam material                                                                                                                              | N/m <sup>2</sup>   |
| Ef     | elastic modulus of follower material                                                                                                                         | N/m <sup>2</sup>   |
| eta0   | lubricant dynamic viscosity at atmospheric pressure and at operating temperature (see Derivation 17)                                                         | N s/m <sup>2</sup> |
| fol    | follower type specified as 'TFlat', 'TDome', 'TRoll', 'SFlat', 'SDome' or 'SRoll' (see Table 4.1)                                                            | —                  |
| fx     | direct stress component in x direction (see Derivation 6)                                                                                                    | N/m <sup>2</sup>   |

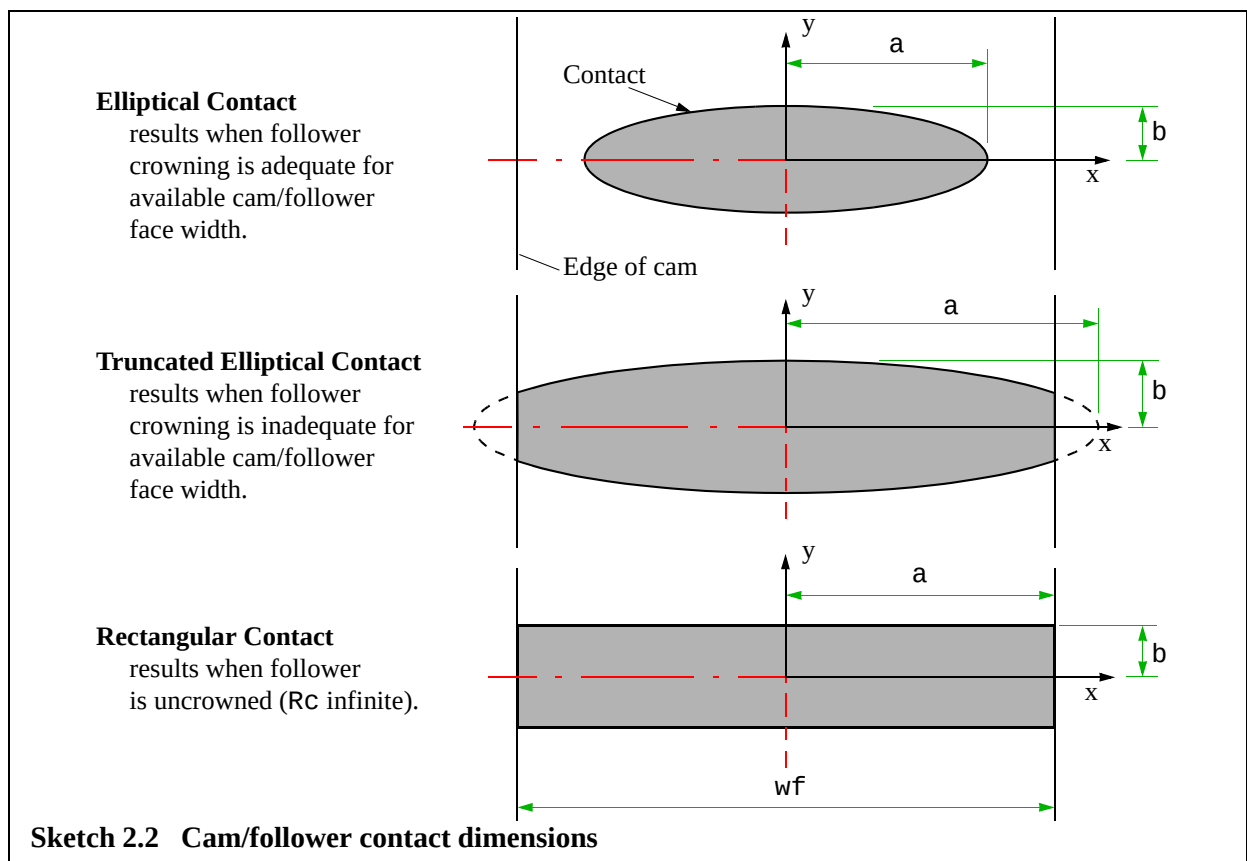
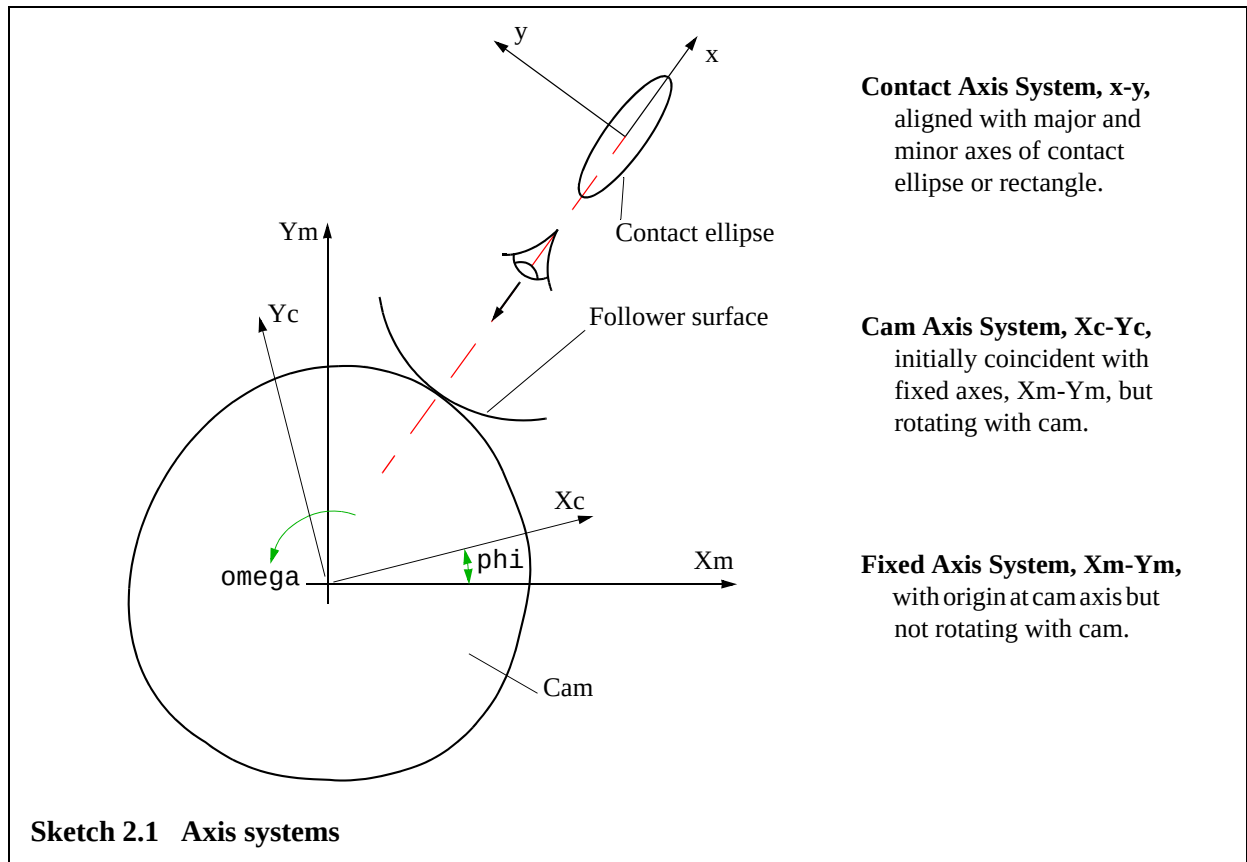
|                        |                                                                                                                               |                  |
|------------------------|-------------------------------------------------------------------------------------------------------------------------------|------------------|
| $f_y$                  | direct stress component in y direction (see Derivation 6)                                                                     | $\text{N/m}^2$   |
| $f_z$                  | direct stress component in z direction (see Derivation 6)                                                                     | $\text{N/m}^2$   |
| $H_t$                  | translating follower total movement                                                                                           | m                |
| $h_{\text{Min}}$       | minimum lubricant film thickness                                                                                              | m                |
| $h_P$                  | translating follower displacement over a cam portion                                                                          | m                |
| $I_{\text{fol}}$       | swinging follower mass moment of inertia about pivot axis                                                                     | $\text{kg m}^2$  |
| $I_{\text{rol}}$       | mass moment of inertia of follower roller about bearing axis                                                                  | $\text{kg m}^2$  |
| $k_C$                  | thermal conductivity of cam material                                                                                          | $\text{W/m K}$   |
| $k_F$                  | thermal conductivity of follower material                                                                                     | $\text{W/m K}$   |
| $k_{\text{Sc}}$        | compression spring stiffness                                                                                                  | $\text{N/m}$     |
| $k_{\text{St}}$        | torsion spring stiffness                                                                                                      | $\text{N m/rad}$ |
| $L$                    | swinging follower pivot/dome centre distance (see Table 4.2)                                                                  | m                |
| $\lambda$              | specific film thickness = $h / (R_q C^2 + R_q F^2)^{1/2}$                                                                     | —                |
| $\lambda_{\text{wDB}}$ | name of cam laws database                                                                                                     | —                |
| $\text{load}$          | load expressions block name                                                                                                   | —                |
| $\text{loadDB}$        | name of external loads database                                                                                               | —                |
| $\log F$               | name of parameters log file                                                                                                   | —                |
| $\log S$               | list of symbols of parameters to log                                                                                          | —                |
| $m_{\text{fol}}$       | equivalent translating follower mass                                                                                          | kg               |
| $\text{motF}$          | name of motion file (see Section 4.2)                                                                                         | —                |
| $n_{\text{Grid}}$      | number of steps for stress distributions                                                                                      | —                |
| $N_r$                  | number of revolutions of follower roller from start of motion                                                                 | —                |
| $\omega$               | rotational velocity of cam taken as positive anticlockwise (see Sketch 2.1)                                                   | rev/s            |
| $\omega_{\text{gF}}$   | absolute angular velocity of follower roller                                                                                  | rad/s            |
| $\omega_{\text{gFD}}$  | absolute angular acceleration of follower roller                                                                              | $\text{rad/s}^2$ |
| $\omega_{\text{gR}}$   | angular velocity of follower roller relative to follower                                                                      | rad/s            |
| $P_{\text{sp}}$        | compression spring preload force                                                                                              | N                |
| $P_b$                  | follower roller bearing load                                                                                                  | N                |
| $P_c$                  | total closure force on translating follower = $(P_e + P_s)$                                                                   | N                |
| $P_e$                  | external closure force on translating follower arising from loading scheme specified in external loads file (see Section 4.3) | N                |
| $P_m$                  | follower roller bearing mean load                                                                                             | N                |
| $P_n$                  | inertial force of translating follower taken as positive when tending to assist closure of cam and follower                   | N                |
| $P_s$                  | spring closure force on translating follower arising from spring parameters specified in input data file (see Section 4.3)    | N                |

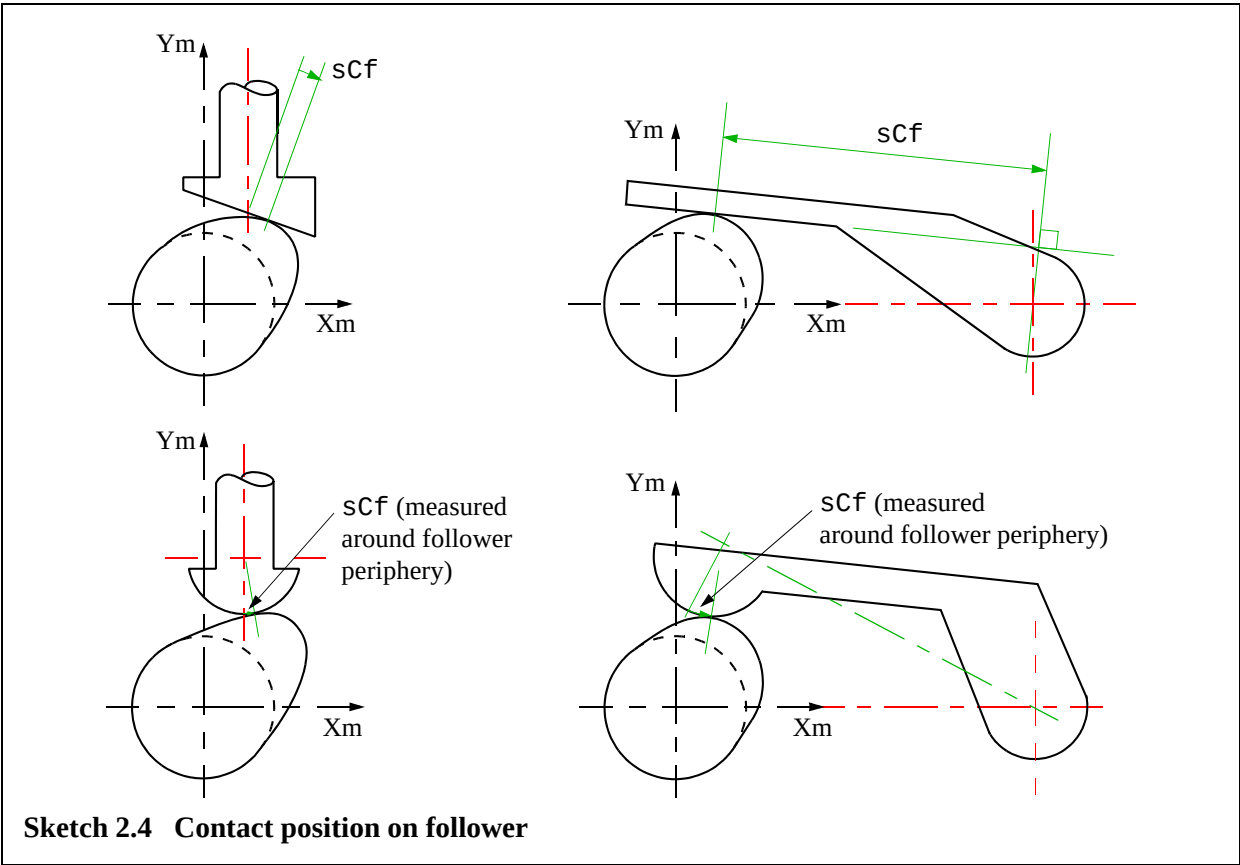
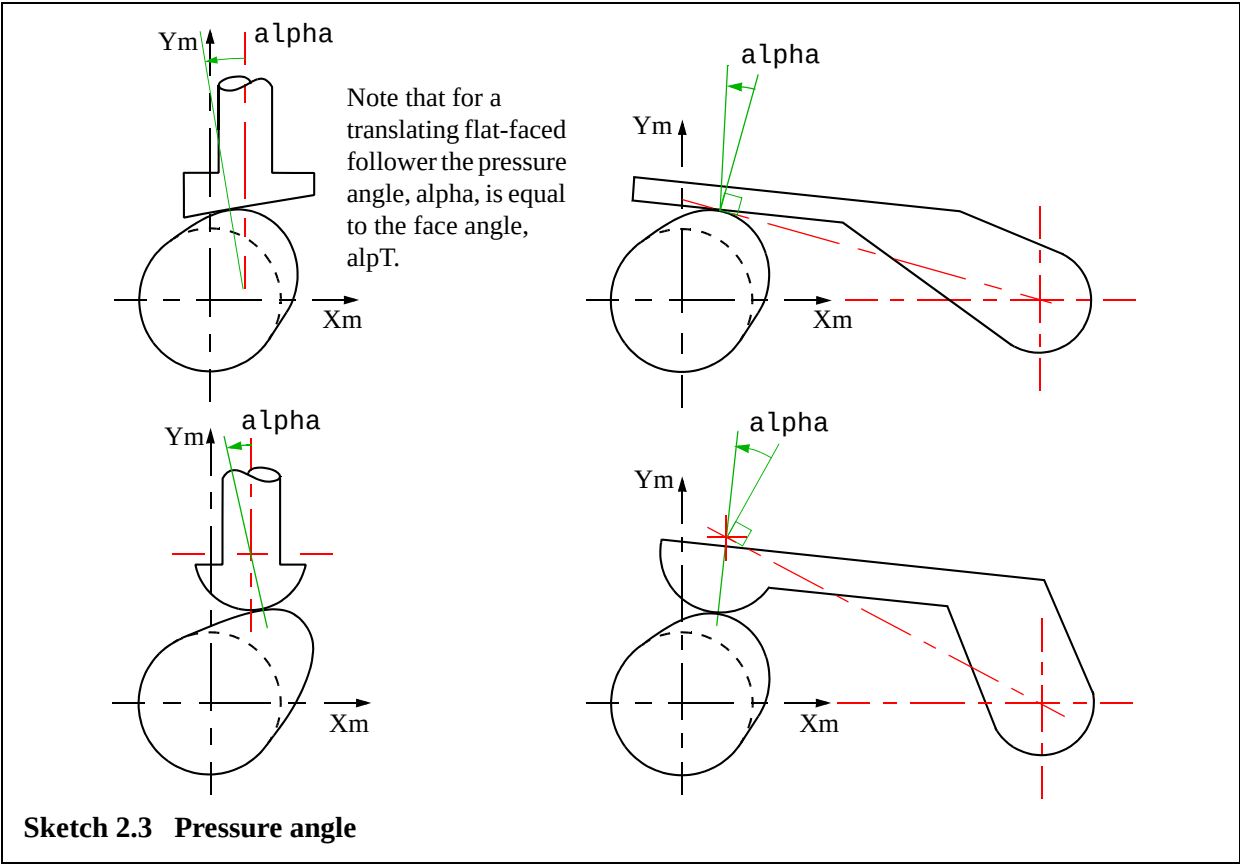
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|        |                                                                                                                         |                    |
|--------|-------------------------------------------------------------------------------------------------------------------------|--------------------|
| Psp    | compression spring preload force                                                                                        | N                  |
| p1Dot  | angular velocity of swinging follower measured positive in rise direction                                               | rad/s              |
| p2Dot  | angular acceleration of swinging follower measured positive in rise direction                                           | rad/s <sup>2</sup> |
| p3Dot  | angular jerk of swinging follower measured positive in rise direction                                                   | rad/s <sup>3</sup> |
| pD1Phi | differential of angular displacement of swinging follower with respect to cam angle measured positive in rise direction | –                  |
| pD2Phi | second differential of displacement of swinging follower with respect to cam angle measured positive in rise direction  | 1/rad              |
| pD3Phi | third differential of displacement of swinging follower with respect to cam angle measured positive in rise direction   | 1/rad <sup>2</sup> |
| phi    | rotation angle of cam from start of motion measured positive in direction of cam rotation (see Sketch 2.1)              | degree             |
| phiBot | starting cam angle for logging of parameters                                                                            | degree             |
| phiCp  | polar co-ordinate angle of contact in fixed axes, Xm-Ym, defined in Sketch 2.1                                          | degree             |
| phiCs  | polar co-ordinate angle of contact in cam axes, Xc-Yc, defined in Sketch 2.1                                            | degree             |
| phiP   | angular extent of cam portion                                                                                           | degree             |
| phiTop | ending cam angle for logging of parameters                                                                              | degree             |
| Po     | maximum Hertzian pressure                                                                                               | N/m <sup>2</sup>   |
| power  | averaged driving power                                                                                                  | W                  |
| psiF   | angular displacement of follower (from psi0 datum) measured positive in rise direction                                  | degree             |
| psiP   | swinging follower displacement over cam portion                                                                         | degree             |
| psiT   | swinging follower total angular movement                                                                                | degree             |
| psiM   | angular displacement of follower from Xm axis                                                                           | degree             |
| psi0   | swinging follower motion datum                                                                                          | degree             |
| Py     | tangential contact force                                                                                                | N                  |
| Pz     | normal contact force                                                                                                    | N                  |
| Qc     | cam driving torque                                                                                                      | N m                |
| Qe     | equivalent shear stress (see Derivation 6)                                                                              | N/m <sup>2</sup>   |
| QeMax  | maximum equivalent shear stress                                                                                         | N/m <sup>2</sup>   |
| Qo     | orthogonal shear stress                                                                                                 | N/m <sup>2</sup>   |
| Qxy    | shear stress component in x plane, y direction (see Derivation 6)                                                       | N/m <sup>2</sup>   |
| Qyz    | shear stress component in y plane, z direction (see Derivation 6)                                                       | N/m <sup>2</sup>   |
| Qzx    | shear stress component in z plane, x direction (see Derivation 6)                                                       | N/m <sup>2</sup>   |

|        |                                                                                                                             |                    |
|--------|-----------------------------------------------------------------------------------------------------------------------------|--------------------|
| Rc     | crown radius of follower (see Table 4.2)                                                                                    | m                  |
| Return | cam law name for return portion (see Section 4.2)                                                                           | –                  |
| Rf     | roller or dome radius (see Table 4.2)                                                                                       | m                  |
| Rise   | cam law name for rise portion (see Section 4.2)                                                                             | –                  |
| RqC    | RMS (root mean square) roughness of cam surface                                                                             | m                  |
| RqF    | RMS (root mean square) roughness of follower surface                                                                        | m                  |
| rCp    | polar co-ordinate radius of contact point                                                                                   | m                  |
| rhoCc  | volumetric heat capacity of cam material                                                                                    | J/m <sup>3</sup> K |
| rhoCf  | volumetric heat capacity of follower material                                                                               | J/m <sup>3</sup> K |
| rMu    | coefficient of kinetic friction                                                                                             | –                  |
| sCf    | contact point distance on follower (see Sketch 2.4)                                                                         | m                  |
| sigC   | Poisson's ratio of cam material                                                                                             | –                  |
| sigF   | Poisson's ratio of follower material                                                                                        | –                  |
| step   | cam rotation step size                                                                                                      | degree             |
| Tc     | total closure moment on swinging follower = (Te + Ts)                                                                       | N m                |
| Te     | external closure moment on swinging follower arising from loading scheme specified in external loads file (see Section 4.3) | N m                |
| Tf     | Blok flash temperature rise for contact (see Derivation 19)                                                                 | K                  |
| Tmax   | maximum tensile stress on perimeter of contact ellipse                                                                      | N/m <sup>2</sup>   |
| Tn     | inertial moment of swinging follower taken as positive when tending to assist closure of cam and follower                   | N m                |
| Ts     | spring closure moment on swinging follower arising from spring parameters specified in input data file (see Section 4.3)    | N m                |
| Tsp    | torsion spring preload moment                                                                                               | N m                |
| theta  | angle of radius vector to point on perimeter of contact area measured positive anticlockwise from x-axis (see Section 7.1)  | degree             |
| time   | elapsed time from start of cam rotation                                                                                     | s                  |
| u      | normalised input rotation of cam                                                                                            | –                  |
| uEntr  | lubricant entrainment velocity = (yDotC + yDotF)/2                                                                          | m/s                |
| u0     | starting value of normalised input for cam portion                                                                          | –                  |
| u1     | ending value of normalised input for cam portion                                                                            | –                  |
| w      | normalised output displacement of follower                                                                                  | –                  |
| wf     | width of cam/follower face (see Sketch 2.2)                                                                                 | m                  |
| work   | cumulative cam driving work                                                                                                 | J                  |
| x      | major axis ordinate constraint position                                                                                     | m                  |
| xBot   | lower constraint on x for stress distribution                                                                               | m                  |

|        |                                                                                       |                    |
|--------|---------------------------------------------------------------------------------------|--------------------|
| xCp    | x co-ordinate of contact point in fixed axes, $X_m$ - $Y_m$ , defined in Sketch 2.1   | m                  |
| xCs    | x co-ordinate of contact point in cam axes, $X_c$ - $Y_c$ , defined in Sketch 2.1     | m                  |
| xTop   | upper constraint on x for stress distribution                                         | m                  |
| xTmax  | x co-ordinate of location of maximum tensile stress                                   | m                  |
| xQeMax | x co-ordinate of location of maximum equivalent shear stress                          | m                  |
| y      | minor axis ordinate constraint position                                               | m                  |
| yCp    | y co-ordinate of contact point in fixed axes, $X_m$ - $Y_m$ , defined in Sketch 2.1   | m                  |
| yCs    | y co-ordinate of contact point in cam axes, $X_c$ - $Y_c$ , defined in Sketch 2.1     | m                  |
| Y0     | translating follower motion datum                                                     | m                  |
| y1Dot  | velocity of translating follower                                                      | m/s                |
| y2Dot  | acceleration of translating follower                                                  | m/s <sup>2</sup>   |
| y3Dot  | jerk of translating follower                                                          | m/s <sup>3</sup>   |
| yBot   | lower constraint on y for stress distribution                                         | m                  |
| yD1Phi | differential of displacement of translating follower with respect to cam angle        | m/rad              |
| yD2Phi | second differential of displacement of translating follower with respect to cam angle | m/rad <sup>2</sup> |
| yD3Phi | third differential of displacement of translating follower with respect to cam angle  | m/rad <sup>3</sup> |
| yDotC  | surface velocity of cam relative to contact point                                     | m/s                |
| yDotF  | surface velocity of follower relative to contact point                                | m/s                |
| yF     | displacement of follower from Y0 datum                                                | m                  |
| yM     | displacement of follower from $X_m$ axis                                              | m                  |
| yTmax  | y co-ordinate of location of maximum tensile stress                                   | m                  |
| yTop   | upper constraint on y for stress distribution                                         | m                  |
| yQeMax | y co-ordinate of location of maximum equivalent shear stress                          | m                  |
| z      | depth axis ordinate constraint position                                               | m                  |
| zBot   | lower constraint on z for stress distribution                                         | m                  |
| zQeMax | z co-ordinate of location of maximum equivalent shear stress                          | m                  |
| zQoMax | z co-ordinate of location of maximum orthogonal shear stress change                   | m                  |
| zTop   | upper constraint on z for stress distribution                                         | m                  |
| zTmax  | z co-ordinate of location of maximum tensile stress                                   | m                  |





## 3. RUNNING THE PROGRAM

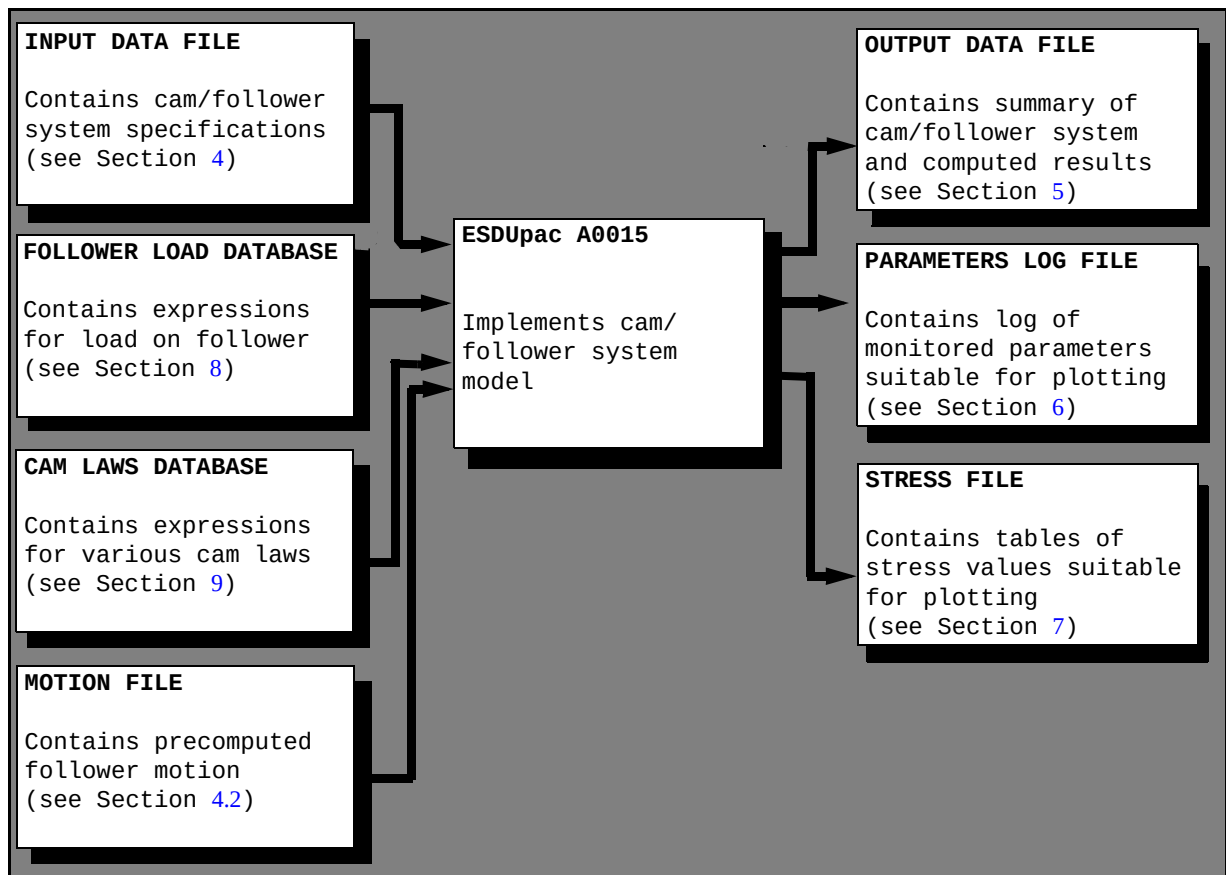
The supplied executable version of the ESDUpac program is suitable for Microsoft Windows operating systems.

To run the executable version of the program from the keyboard, type the program name<sup>†</sup>, A0015V10, at the operating system prompt and press return. The program will prompt for the name of the input data file and the name of the output data file. Alternatively, the name of the input data file and the name of the output data file can be specified on the command line using the operating system redirection symbols as in

```
A0015V10 < EXP1.IN > EXP1.OUT
```

If a problem occurs in reading the data from the input file or if the data are invalid in any way, error messages are recorded in the output file. These error messages describe the error and, where applicable, indicate the line number at which the error occurred in the input data file.

A number of example input data files are supplied with the program (files with the extension ".IN"). These input files and the corresponding output data files (with the extension ".OUT") can be examined using a text editor. A cam laws database file, a follower load database file, and a motion file are also provided. These files too can be examined using a text editor. All of these files are described in the following sections and an overview of the purpose of each type of file is shown here.



<sup>†</sup> The program name used here is that of Version 1.0 (V10) which may not be the latest.

## 4. THE INPUT DATA FILE

The input data file provides the specification of the cam and follower system that is to be analysed. Input data files are prepared using a text editor and, in most cases, new input files will be produced by editing existing input files. An example input file, which incorporates comments for documentation purposes, is shown here.

```

ESDU A0015
* Follower specification
* ~~~~~
fol      follower type          = TDome

E        follower offset        = 0.01   m
Rf       follower dome radius   = 0.05   m
Rc       follower crown radius  = 0.5    m

mFol     follower mass          = 0.5    kg

Y0       follower motion datum  = 0.1    m
Psp      follower spring preload = 50     N

* Follower motion specification
* ~~~~~
omega    cam rotational speed   = 10     rev/s

Dwell    dwell cam portion      = Dwell
phiP     extent of portion      = 45     degree

Rise     rise cam portion        = ModTrap
phiP     extent of portion      = 90     degree
hP       movement of portion    = 0.01   m

Dwell    dwell cam portion      = Dwell
phiP     extent of portion      = 45     degree

Return   return cam portion     = ModTrap
phiP     extent of portion      = 180    degree
hP       movement of portion    = 0.01   m

* Parameters log
* ~~~~~
logS     logged parameters      = phi, QeMax
step     cam rotational step    = 1.0    degree
    
```

In this example input file, the input parameters have been grouped under separate headings inserted as comments (lines starting with the "\*" character). It will be observed that the section headed "Follower motion specification" consists of separate blocks for each portion of the cam profile which is, in this particular example file, that of a DRDR cam consisting of a dwell portion, followed by a rise, another dwell, and then a return. Apart from the requirement that these blocks defining each portion of the cam appear in the order in which the cam is to rotate, all other input parameters can be specified in any order whatsoever. However, the first non-comment line of the file must identify the name of the ESDUpac program, A0015 in this case, that is to be used for the analysis. The following observations apply (a formal specification of the input file format is given in Appendix A).

- (i) All lines beginning with an asterisk, "\*", are comment lines. Such comments can be freely inserted for documentation purposes.
- (ii) The first non-comment line in the input file specifies the name of the ESDUpac program that is to be used for the analysis. The keyword "ESDU" is used for this purpose and the line must be present in all input files.
- (iii) Each input parameter has an identifying symbol, which is case insensitive. The explanatory text following the parameter symbol may be omitted in which case the "=" sign is not strictly necessary.
- (iv) Units have been stated in the file purely for documentation purposes. All text following the actual numerical value is ignored.

Although recommended, it is not mandatory that input files be commented and an undocumented version of the above example input file is shown here which consists of just a series of symbol-value pairs.

|            |            |
|------------|------------|
| ESDU A0015 |            |
| fol        | TDome      |
| E          | 0.01       |
| Rf         | 0.05       |
| Rc         | 0.5        |
| mFol       | 0.5        |
| Y0         | 0.1        |
| Psp        | 50         |
| omega      | 10         |
| Dwell      | Dwell      |
| phiP       | 45         |
| Rise       | ModTrap    |
| phiP       | 90         |
| hP         | 0.01       |
| Dwell      | Dwell      |
| phiP       | 45         |
| Return     | ModTrap    |
| phiP       | 180        |
| hP         | 0.01       |
| logS       | phi, QeMax |
| step       | 1.0        |

An additional means of documenting the input file which involves appending comments to the ends of parameter specification lines with the "!" character, can be used as shown here.

```

ESDU A0015

* Follower specification
* ~~~~~
fol   = TDome           !Follower is a translating domed type

E     = 0.01    m       !Follower offset
Rf    = 0.05    m       !Follower dome radius
Rc    = 0.5     m       !Follower crown radius

mFol  = 0.5     kg      !Follower mass

Y0    = 0.1     m       !Follower motion datum
Psp   = 50      N       !Follower spring preload

* Follower motion specification
* ~~~~~
omega = 10        rev/s  !Cam rotational speed

Dwell = Dwell
phiP  = 45        degree !An initial dwell portion
                        !of 45 degree extent

Rise  = ModTrap
phiP  = 90        degree !A rise portion
                        !of 90 degree extent
hP    = 0.01     m       !and 0.01 m movement

Dwell = Dwell
phiP  = 45        degree !An intermediate dwell portion
                        !of 45 degree extent

Return = ModTrap
phiP   = 180      degree !A return portion
                        !of 180 degree extent
hP     = 0.01     m       !and 0.01 m movement

* Parameters log
* ~~~~~
logS   = phi, QeMax      !Monitor parameters phi and QeMax
step   = 1.0            !every 1 degree of cam rotation
    
```

As with other ESDUpac programs in the Tribology Series, ESDUpac A0015 allows additional cases to be appended to the initial input data with the use of the "\$CASE" keyword. Any number of these additional cases can be appended and they, effectively, allow the ESDUpac program to repeat the calculations with the initial input data modified in some way. The extra case shown here could be appended to the previous example input file to allow the effect of altering the cam speed and motion datum to be investigated.

```

$CASE

* Investigate increase of cam speed and decrease of base circle
* ~~~~~
omega = 15        rev/s

Y0    = 0.08     m
    
```

Additional cases appended with \$CASE provide a convenient way of performing a sensitivity analysis in which the effect of changing one or, perhaps, two parameters would be explored as shown in Example 6 (Section 10.6). Example 7 (Section 10.7) illustrates another use of the \$CASE keyword.

In this ESDUpac program, default values are provided for certain input parameters (see Section 4.9) and, accordingly, not all input parameters need be specified. Some other parameters can be left unspecified if they are not relevant for the application being considered. An input parameter can be left unspecified in one of three ways.

- (i) Put a question mark, "?", in place of the parameter value.
- (ii) Comment-out the parameter specification by placing an asterisk, "\*", or an exclamation, "!", at the start of the line.
- (iii) Omit the parameter specification entirely.

## 4.1 Cam Follower

The type of follower is specified by the `fol` symbol in the input file. In the example shown here a translating domed follower has been specified.

```
* Follower specification
* ~~~~~
fol    follower type      = TDome
```

ESDUpac A0015 allows six types of follower as listed in Table 4.1 and described in Table 4.2.

| TABLE 4.1 TYPES OF CAM FOLLOWER |                                 |
|---------------------------------|---------------------------------|
| Follower type identifier        | Description                     |
| TFlat                           | Translating flat-faced follower |
| TDome                           | Translating domed follower      |
| TRoll                           | Translating roller follower     |
| SFlat                           | Swinging flat-faced follower    |
| SDome                           | Swinging domed follower         |
| SRoll                           | Swinging roller follower        |

The parameters that must be specified depend on the type of follower selected. Table 4.2 indicates the dimensional parameters that must be specified for the various types. Note that with swinging followers, the pivot is always taken to be to the right of the cam axis and directly on the  $X_m$  axis.

It is good practice to provide a crown radius for the follower,  $R_c$ , to ensure a true elliptical contact area free from the sharp end-effect stresses that can occur with a rectangular contact. If an uncrowned follower is to be analysed,  $R_c$  should be specified as infinite using the special notation shown in the following input file fragment. Without crowning, the length of the resulting rectangular contact is determined by the available width of the follower or cam face,  $w_f$ , which should also be specified.

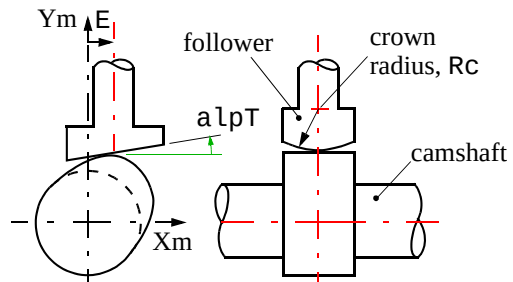
```
* Uncrowned follower specification
* ~~~~~
fol    follower type      = TDome
Rc     crown radius       = 00      !uncrowned (infinite radius)
wf     width of follower  = 0.01    m
```

**TABLE 4.2 DIMENSIONAL PARAMETERS FOR THE SIX FOLLOWER TYPES**

Translating flat-faced follower, **TFlat**

- E follower offset
- $\alpha_{lpT}$  face angle
- RC crown radius

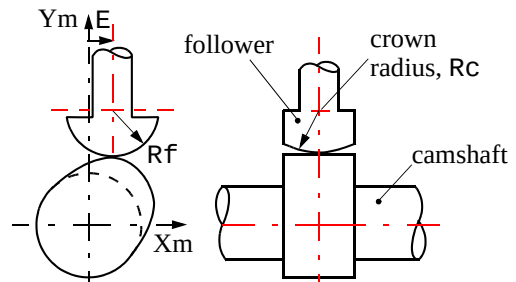
Note: Follower offset, E, and face angle,  $\alpha_{lpT}$ , can be positive, as in the sketch, or negative



Translating domed follower, **TDome**

- E follower offset
- Rf dome radius
- RC crown radius

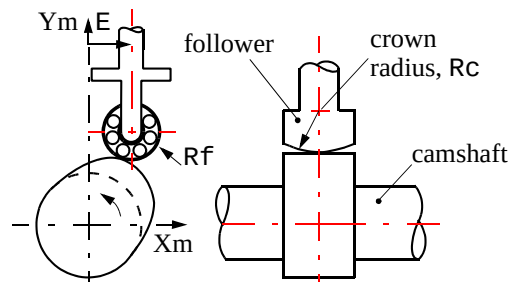
Note: Follower offset, E, can be positive as in the sketch, or negative.



Translating roller follower, **TRoll**

- E follower offset
- Rf roller radius
- RC crown radius

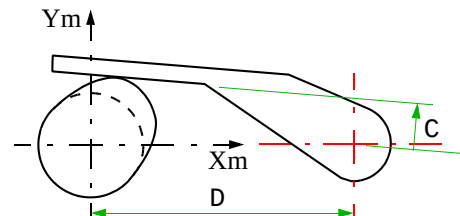
Note: Follower offset, E, can be positive, as in the sketch, or negative



Swinging flat-faced follower, **SFlat**

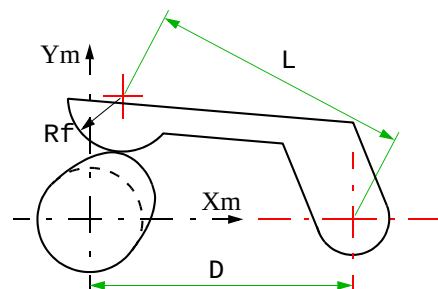
- D pivot/cam axis distance
- C crank length
- RC crown radius (see TFlat)

Note: Crank length, C, can be positive, as in the sketch, or negative with the flat face of the follower below the pivot.



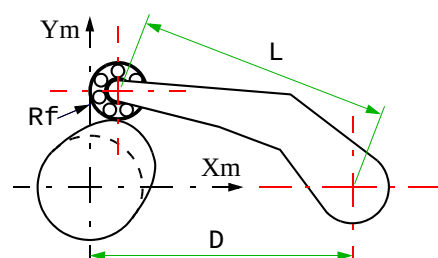
Swinging domed follower, **SDome**

- D pivot/cam axis distance
- L pivot/dome centre distance
- Rf dome radius
- RC crown radius (see TDome)



Swinging roller follower, **SRoll**

- D pivot/cam axis distance
- L pivot/roller centre distance
- Rf roller radius
- RC crown radius (see TRoll)



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The inertia of the follower is specified by the follower mass,  $m_{Fol}$ , in the case of a translating follower, or by the mass moment of inertia about the follower pivot,  $I_{Fol}$ , in the case of a swinging follower. In both cases, an equivalent value should be specified that takes into account the inertia of all moving parts connected to, or driven by, the follower.

ESDUpac A0015 assumes zero slip of a roller follower on the cam surface but issues a warning message if this assumption is invalid. To allow the validity check to be made, the moment of inertia of the roller,  $I_{rol}$ , must be specified as shown in the following example input data fragment. An assumed value of the friction coefficient,  $r_{Mu}$ , must also be specified (see Section 4.4).

```
* Follower specification
* ~~~~~
fol      follower type          =  SRoll

C        crank length           =  0.01    m
D        centre/pivot distance  =  0.070   m
L        pivot/dome centre distance = 0.060   m
Rf       roller radius          =  0.0095   m
Rc       roller crown radius     =  0.5      m

IFol     follower moment of inertia = 0.05    kg m^2
Irol     roller moment of inertia  = 4.6E-6   kg m^2
rMu      coefficient of friction   = 0.01
```

The point, or points, in the cam cycle at which roller slip is likely can be found by logging the critical friction coefficient required to prevent slip,  $c_{Mu}$  (see Section 4.7).

## 4.2 Follower Motion

It is mandatory that the rotational speed of the cam, which is assumed to be constant, is specified in the input file as shown in the following input data fragment.

```
* Follower motion specification
* ~~~~~
omega    cam rotational speed    =  10      rev/s
```

A positive value of omega, as in the example here, implies an anticlockwise rotation of the cam. If required, a negative value can be specified for omega which implies a clockwise rotation of the cam. In general, the geometry of the cam, for a given follower motion, with clockwise rotation is not simply a mirror image of that with anticlockwise rotation and the forces involved may be different.

The motion of the follower and, indirectly, the profile of the cam, can be specified by stipulating the law or laws determining the follower motion as a function of cam rotation. Alternatively, a precomputed follower motion can be imported from a motion file such as can be produced by computer programs in the ESDU Mechanisms Series. If such a file is to be imported, the name of the file must be specified in the input data as shown here (see also Example 6, Section 10.6).

```
* Import from motion file
* ~~~~~
motF     motion file name       =  "CAM1.MOT"
```

If a motion file is not available, the follower motion is specified by defining portions of cam rotation over which the follower motion is dictated by a particular cam law. Each of these portions must be declared as being a Rise portion in which the follower displacement increases with cam rotation, a Return portion in

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which the follower displacement decreases with cam rotation, or a Dwell in which the follower displacement remains constant. The angular extent of each portion,  $\phi_{iP}$ , and the follower displacement over the portion,  $h_P$  for a translating follower or  $\psi_{iP}$  for a swinging follower, must also be specified. Note that both  $h_P$  and  $\psi_{iP}$  are always specified as positive values irrespective of whether the portion is a Rise or Return. In the following example input file fragment, a Rise portion extending over 57 degree of cam rotation has been specified that follows the well known modified trapezoidal acceleration cam law (see Derivation 8). The portion provides a follower displacement of 0.01 m.

```
* Modified trapezoidal rise portion
* ~~~~~
Rise = ModTrap

    phiP  extent of portion    = 57      degree
    hP    movement of portion  = 0.01    m
```

Expressions for cam laws are held in a database and each law has an identifying name, such as the `ModTrap` identifier used in the above input file fragment. By default, ESDUpac A0015 uses the "CAMLAWS.DAT" database supplied with the program but other, user constructed, databases can be used. If an alternative cam laws database is to be used, the name of the file must be specified in the input file as shown in the following input file fragment. The cam laws included in the supplied database are listed in Table 4.3.

```
* Use an alternative cam laws database
* ~~~~~
lawDB = 'MYLAWS.DAT'
```

Note that the specification, if present, must appear before any Rise, Return or Dwell cam portions are declared. If the name of a cam laws database is specified after any of the cam portion declarations, an error message is issued and the ESDUpac program is terminated.

**TABLE 4.3 CAM LAWS INCLUDED IN THE SUPPLIED DATABASE, CAMLAWS.DAT**

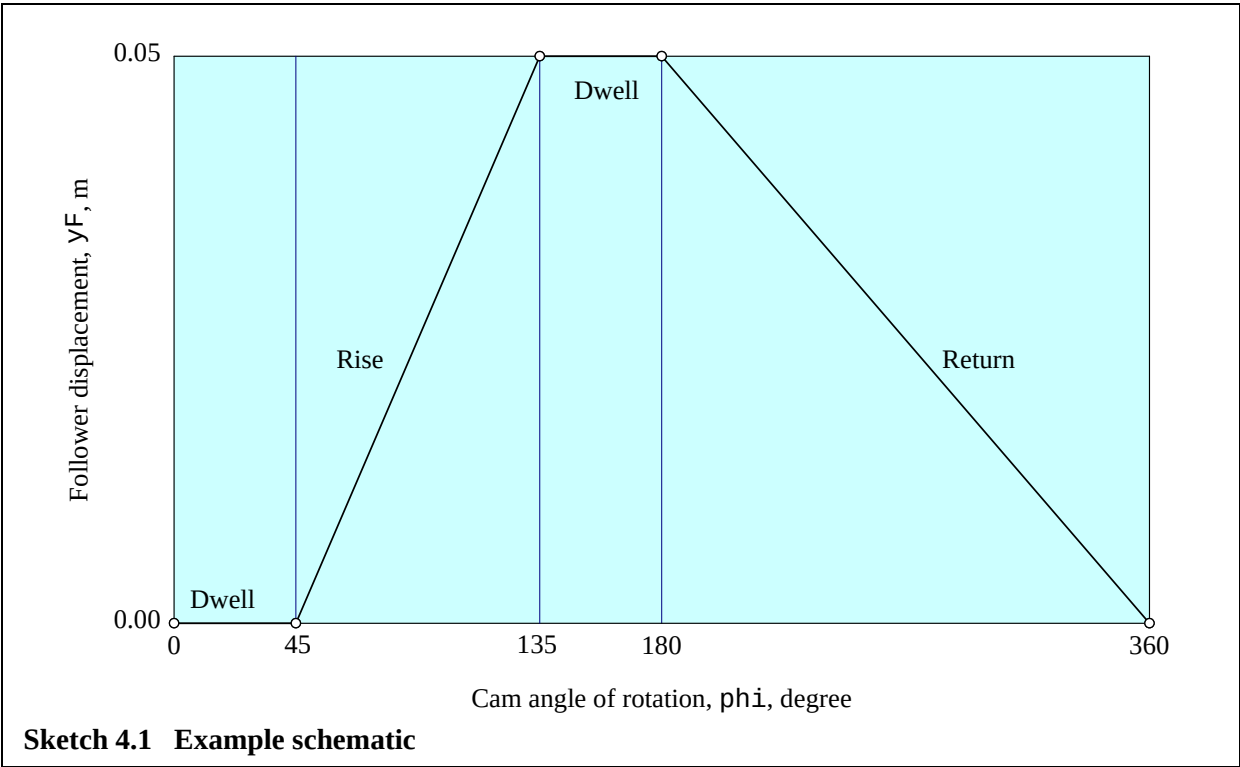
| Identifier | Full name                                    |
|------------|----------------------------------------------|
| Dwell      | Dwell                                        |
| CVRamp     | Constant velocity ramp                       |
| CARamp     | Constant acceleration ramp                   |
| CJRamp     | Constant jerk ramp                           |
| SHM        | Simple harmonic motion                       |
| Parab      | Parabolic (constant acceleration)            |
| Cycloid    | Cycloidal (sine acceleration)                |
| ModTrap    | Modified trapezoidal acceleration            |
| ModSin     | Modified sine acceleration                   |
| 3HModTrap  | 3-harmonic modified trapezoidal acceleration |
| 3HModSin   | 3-harmonic modified sine acceleration        |
| 3HZero     | 3-harmonic zero-jerk-at-crossover            |
| 2DHarmonic | Double harmonic                              |
| 23Poly     | 2-3 polynomial                               |
| 345Poly    | 3-4-5 polynomial                             |
| 357Poly    | 3-5-7 polynomial                             |
| 369Poly    | 3-6-9 polynomial                             |
| 3711Poly   | 3-7-11 polynomial                            |
| 346Poly    | 3-4-6 polynomial                             |
| 347Poly    | 3-4-7 polynomial                             |
| 356Poly    | 3-5-6 polynomial                             |
| 456Poly    | 4-5-6 polynomial                             |
| 468Poly    | 4-6-8 polynomial                             |
| 4710Poly   | 4-7-10 polynomial                            |
| 4812Poly   | 4-8-12 polynomial                            |
| 3456Poly   | 3-4-5-6 polynomial                           |
| 3579Poly   | 3-5-7-9 polynomial                           |
| 36912Poly  | 3-6-9-12 polynomial                          |
| 371115Poly | 3-7-11-15 polynomial                         |
| 4567Poly   | 4-5-6-7 polynomial                           |
| 46810Poly  | 4-6-8-10 polynomial                          |
| 471013Poly | 4-7-10-13 polynomial                         |
| 481216Poly | 4-8-12-16 polynomial                         |

These cam laws cover a wide range of characteristics which are described in Derivations 8 and 16. The set of cam laws is, of course, only a representative sample of all possible cam laws, but expressions for other laws can be included in a user constructed database if required. The contents of the cam laws database, and the manner in which other databases can be constructed, is described in Section 9.

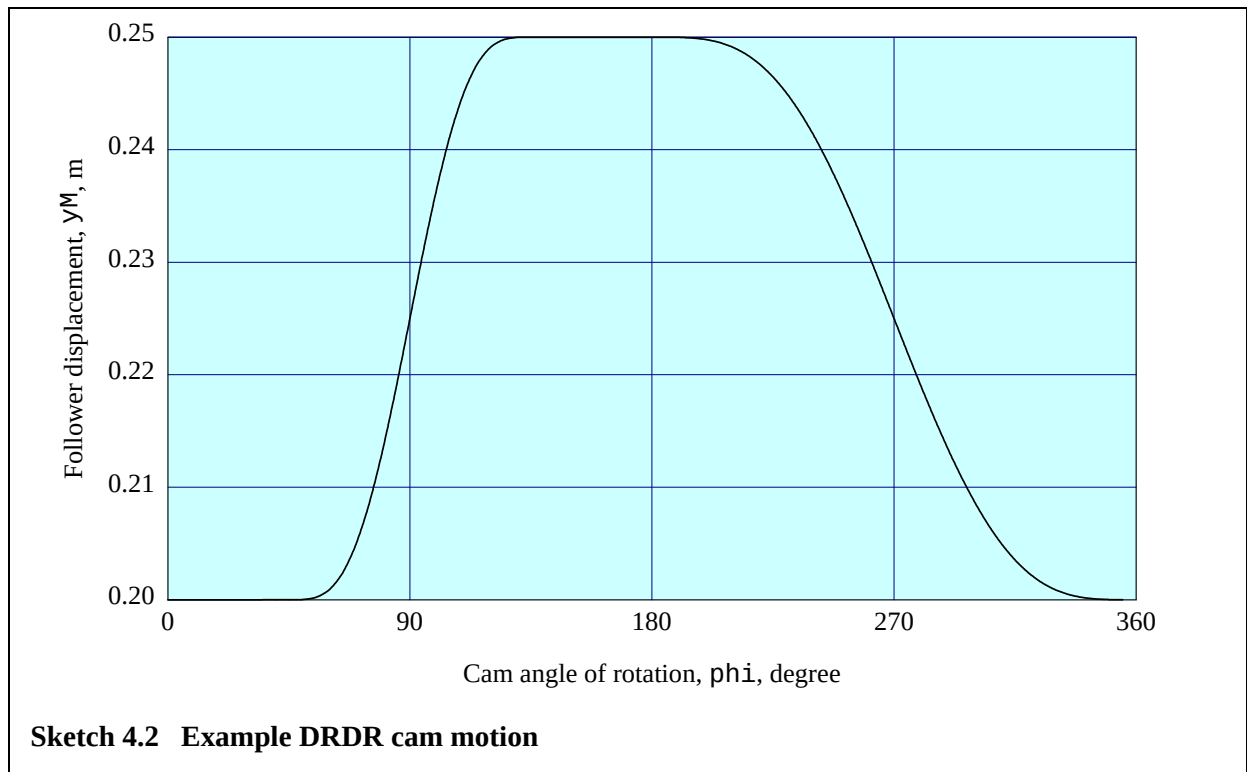
A cam law, such as the ModTrap law specified in the above example, represents the motion of the follower over only a single portion of cam rotation. In general several such portions, possibly using a different cam law for each portion, are required. It is also necessary to specify a datum for the follower motion,  $Y_0$  for a translating follower or  $\psi_0$  for a swinging follower. A follower motion consisting of a dwell, followed by a rise, another dwell, and then a return (a DRDR cam) might be specified as shown in the following input file fragment.

|                                 |                       |   |          |        |
|---------------------------------|-----------------------|---|----------|--------|
| * Follower motion specification |                       |   |          |        |
| * ~~~~~                         |                       |   |          |        |
| Y0                              | follower motion datum | = | 0.2      | m      |
| Dwell                           | dwell cam portion     | = | Dwell    |        |
| phiP                            | extent of portion     | = | 45       | degree |
| Rise                            | rise cam portion      | = | 4567Poly |        |
| phiP                            | extent of portion     | = | 90       | degree |
| hP                              | movement of portion   | = | 0.05     | m      |
| Dwell                           | dwell cam portion     | = | Dwell    |        |
| phiP                            | extent of portion     | = | 45       | degree |
| Return                          | return cam portion    | = | 4567Poly |        |
| phiP                            | extent of portion     | = | 180      | degree |
| hP                              | movement of portion   | = | 0.05     | m      |

When preparing an input file for a cam follower motion, it is often advisable to first prepare a schematic timing diagram an example of which is shown in Sketch 4.1 (see Reference 3).



The actual motion of the follower with the cam specified in the example input data is shown in Sketch 4.2.



In the above example follower motion, a complete cam law has been used to represent each motion segment (a segment corresponds to a complete rise, dwell or return motion). Sometimes, however, portions of two or more laws might be used to construct a single rise or return segment so that special motion requirements can be satisfied (see Derivations 9 and 10). It is then necessary to define which part of each law is to be used by specifying the value of the normalised input rotation at the start and end of each portion,  $u_0$  and  $u_1$ . A cam law is defined over an interval of normalised input rotation,  $u$ , from 0.0 to 1.0 (see Section 9) and so, if only the first half of a law is to be used, for example,  $u_0$  and  $u_1$  would be specified as 0.0 and 0.5 respectively.

In the following input file fragment, the Rise segment of the cam has been specified as consisting of two blended portions of the ModTrap (modified trapezoidal) cam law. The first portion extends over 35 degree of cam rotation and uses the acceleration loop of the law with  $u$  running from 0.0 to 0.5. The second portion extends over 55 degree of cam rotation and uses the deceleration loop of the law with  $u$  running from 0.5 to 1.0. Appropriate follower displacements,  $h_P$ , have been specified for each portion so that the follower movement over the combined portions is equal to a total movement of 0.05 m.

```

* Follower movement
* ~~~~~
Y0    motion datum      = 0.2    m

* Inner dwell portion
* ~~~~~
Dwell = Dwell

    phiP = 45            degree

* Rise segment
* ~~~~~
Rise   = ModTrap

    phiP = 35            degree
    hP   = 0.01944 m
    u0   = 0
    u1   = 0.5

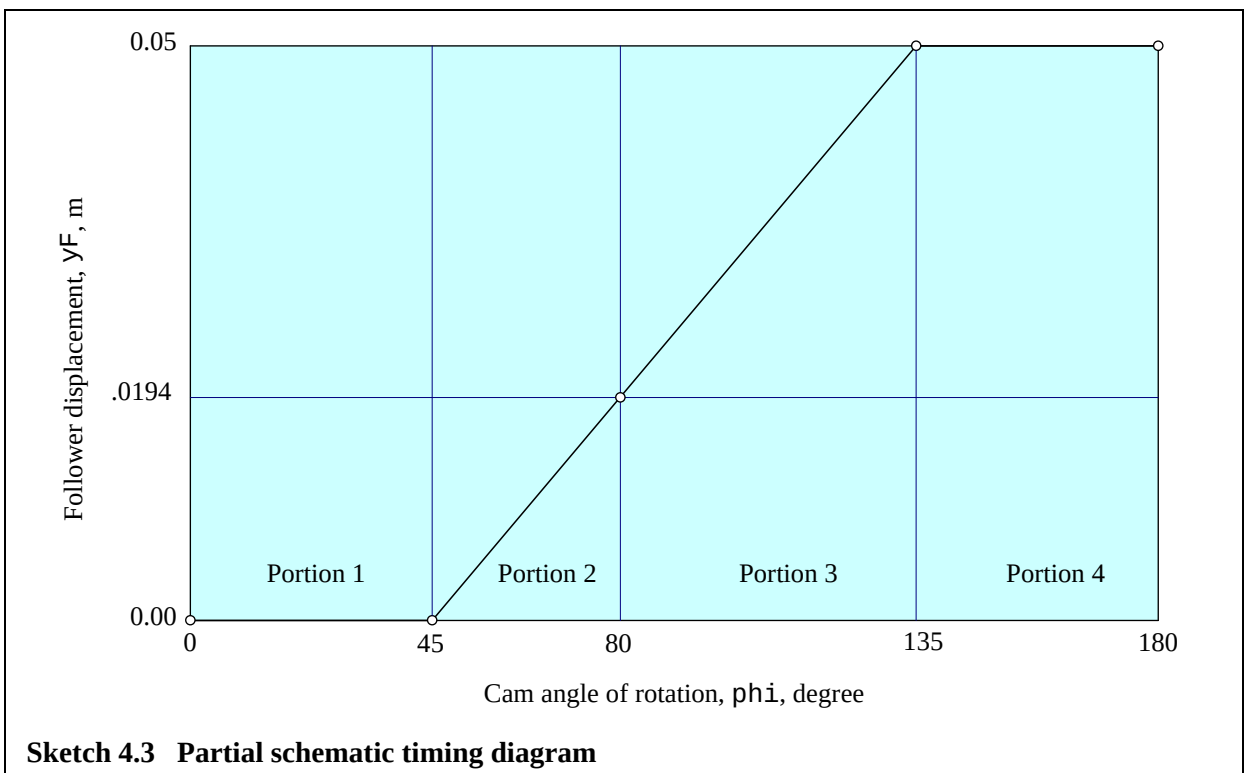
    Rise = ModTrap

    phiP = 55            degree
    hP   = 0.03056 m
    u0   = 0.5
    u1   = 1.0

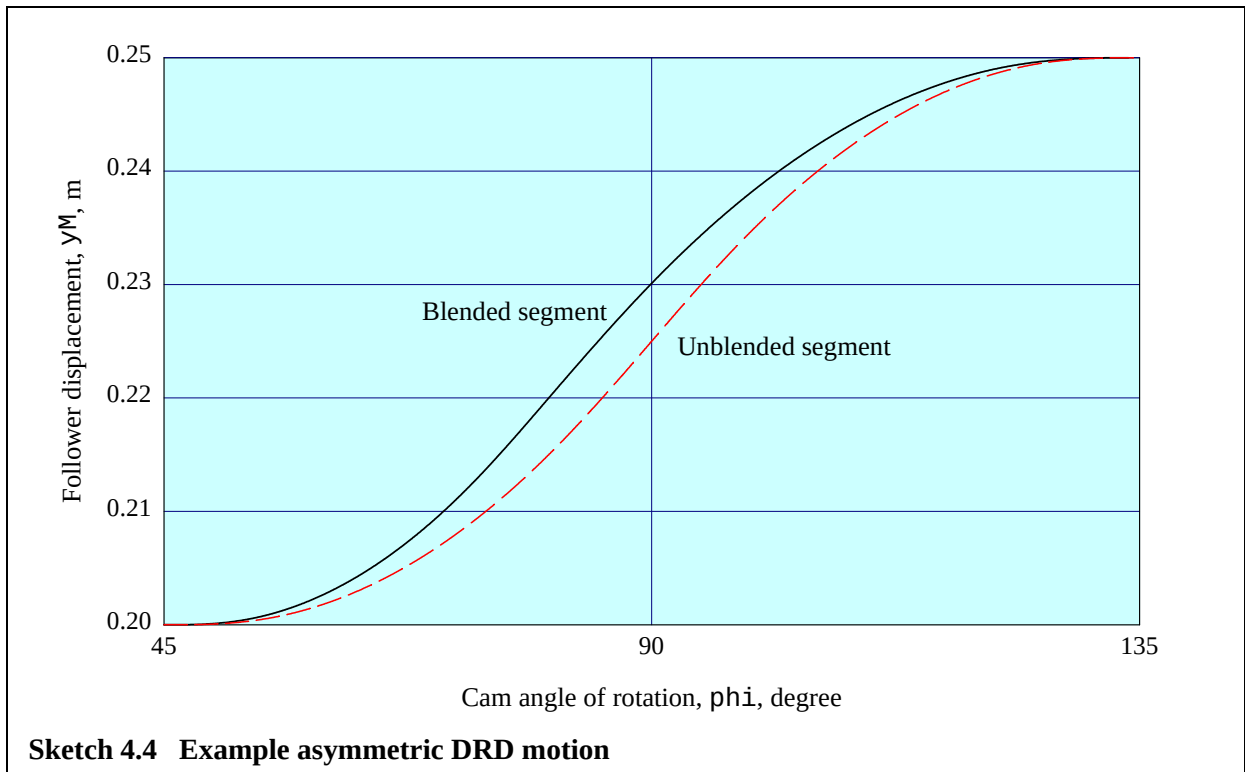
* Outer dwell portion
* ~~~~~
Dwell = Dwell

    phiP = 45            degree
    
```

The partial schematic timing diagram for the example blended motion is shown in Sketch 4.3.



The follower motion provided by the blended rise segment, consisting of portions 2 and 3 in the timing diagram, is compared with that of an unblended ModTrap segment in Sketch 4.4.



When portions of cam laws are used in the manner described, ESDUpac A0015 ensures that the follower displacement is continuous in the transition from one law portion to the next. However, it is still not sufficient simply to join together arbitrarily selected portions of cam laws since the portions used must be carefully selected so that the velocity is also continuous at the joints. Consideration of vibration and follower roller slip can also require that the acceleration be continuous. A procedure for the blending of cam laws is given in Derivations 9 and 10.

## 4.3 Follower Spring and External Loading

The closure force ensuring that the cam and follower remain in contact is usually provided by a spring. A compression spring is assumed with a translating follower and the spring preload and stiffness are specified as shown in the following input file fragment.

```
* Compression spring
* ~~~~~
Psp  compression spring preload force      = 30.0    N
kSc  compression spring stiffness          = 80.0    N/m
```

With a swinging follower, a torsion spring is used and the preload and stiffness are specified as shown in the following input file fragment.

```
* Torsion spring
* ~~~~~
Tsp  torsion spring preload moment          = 30.0    N m
kSt  torsion spring stiffness                = 80.0    N m/rad
```

The spring preload is defined as the force, or moment, exerted by the spring when the follower displacement from the motion datum,  $Y_0$  or  $\psi_0$ , is zero. Specification of the motion datum is described in Section 4.2.

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A spring force might not be the only external force applied to the follower since there can, for example, be position and motion dependent process loads. These additional loads can be specified in a separate loads database file. A loads database file resembles a cam laws database file in that it contains named blocks of expressions and particular blocks are selected by name as shown in the following input file fragment.

```
* Additional follower loads from database
* ~~~~~
loadDB = 'EXLOADS.DAT'
load   = Process1
```

The contents of a follower loads database, and the manner in which such a database can be constructed and extended, is described in Section 8.

## 4.4 Cam and Follower Materials

The program provides default material property values assuming a steel cam and follower (see Table 4.6). Where other materials are to be used for the cam or follower, or where greater accuracy is required, the material property values should be specified in the input file. The elastic moduli of the surface materials of both the cam and the follower,  $E_c$  and  $E_f$ , can be specified as shown in the following input file fragment.

```
* Material properties
* ~~~~~
Ec    elastic modulus of cam surface material = 193.0E9 N/m^2
Ef    elastic modulus of follower material   = 1.9E9  N/m^2
```

The value of Poisson's ratio is, by default, assumed to be 0.3 for both the cam and follower materials. For many contact situations, especially where the tangential loading is small, stress fields tend not to be sensitive to Poisson's ratio. Indeed, the orthogonal shear stress is independent of Poisson's ratio for all contacts. However, where the ratio is known to be different from the default value, it can be specified in the input file as shown here.

```
* Material properties
* ~~~~~
Ec    elastic modulus of cam surface material = 193.0E9 N/m^2
Ef    elastic modulus of follower material   = 1.9E9  N/m^2

sigF  Poisson's ratio of follower material   = 0.4
```

Friction between the cam and the follower can provide a tangential loading at the contact in addition to the normal reaction force. In the following input file fragment, a value of friction that might apply with an unlubricated polymer follower has been specified. If left unspecified, the friction is assumed to be zero and the contact loading is then purely normal.

```
* Material properties
* ~~~~~
Ec    elastic modulus of cam surface material = 193.0E9 N/m^2
Ef    elastic modulus of follower material   = 1.9E9  N/m^2

sigF  Poisson's ratio of follower material   = 0.4

rMu   coefficient of friction                 = 0.3
```

With flat-faced and domed followers, frictional energy dissipation at the contact represents a driving power loss and also results in a temperature rise in the contact above the bulk temperature. Properties that are important in determining this temperature rise are the thermal conductivity and volumetric heat capacity of the cam and follower materials. Non-default values for these properties have been specified in the

following input file fragment.

```
* Thermal properties
* ~~~~~
rhoCc    volumetric heat capacity of cam material      = 3.3E6 J/m^3 K
rhoCf    volumetric heat capacity of follower material = 3.0E6 J/m^3 K

kC       thermal conductivity of cam material          = 15  W/m K
kF       thermal conductivity of follower material      = 50  W/m K
```

By default, ESDUpac A0015 determines the stresses on the surface and within the material of the cam. When the material properties of both the cam and follower are identical, the stress field in one body can be obtained by an appropriate rotation of the field in the other. Where the material properties differ, however, and where it is required to examine the follower stresses, a specification such as the following should be included in the input file.

```
body      =    follow
```

## 4.5 Lubricant Properties

Where a liquid lubricant is present, ESDUpac A0015 can be used to log the film thickness of the lubricant entrained into the contact. By default the program assumes approximate lubricant properties appropriate for a typical light mineral oil at a bulk temperature of about 30 degC. Where greater accuracy is required, or where the lubricant is known to have properties that differ from these assumed defaults, property values should be specified as shown in the following input file fragment.

```
* Lubricant properties
* ~~~~~
eta0      lubricant dynamic viscosity                  = 360.0E-3 N s/m^2
alp0      pressure exponent of lubricant viscosity      = 15.9E-9  m^2/N
```

The lubricant dynamic viscosity value specified should be for ambient pressure and a temperature representative of the expected operating surface temperature of the cam and follower. Guidance on values for both the dynamic viscosity and the pressure exponent of lubricant viscosity is given in Derivation 17.

Values can also be specified for the surface roughness of the cam and follower, where these are known, so that the specific film thickness (see Derivation 17) can be more accurately calculated.

```
* Surface roughnesses
* ~~~~~
RqC       RMS roughness of cam surface                 = 0.7E-6  m
RqF       RMS roughness of follower surface             = 0.5E-6  m
```

Typical values of RMS surface roughness are shown here.

### Typical RMS (root mean square) Surface Roughness Values

| Method of finishing | Initial value, $\mu\text{m}$ | Run-in value, $\mu\text{m}$ |
|---------------------|------------------------------|-----------------------------|
| Milling             | 1.6 to 3.3                   | 0.8 to 1.6                  |
| Hobbing or shaping  | 0.8 to 1.6                   | 0.6 to 1.2                  |
| Shaving or grinding | 0.5 to 1.0                   | 0.4 to 0.8                  |
| Lapping             | 0.4 to 0.7                   | 0.3 to 0.6                  |
| Honing              | 0.2 to 0.4                   | 0.1 to 0.3                  |

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## 4.6 Constraints

ESDUpac A0015 can be used to determine the instantaneous contact stresses in an operating cam (see Sections 4.7 and 4.8) and to locate the critical stress points. By default, no constraints are placed on the search for these critical stress points which, depending on the loading conditions, might correspond to a surface or sub-surface stress and be located directly under the nominal contact point or be offset by a small distance. If required, constraints can be placed on the search by specifying values for one or more of the ordinates  $x$ ,  $y$  and  $z$ .

To constrain the search for critical stress points to a plane, specify a value for one of the ordinates  $x$ ,  $y$  or  $z$ . The specified ordinate will then be held constant during the search. For example, if it is required to locate the critical stress points at a depth of 0.0001 m below the surface, the following specification would be added to the input file.

|     |                             |   |        |   |
|-----|-----------------------------|---|--------|---|
| $z$ | depth below surface of body | = | 0.0001 | m |
|-----|-----------------------------|---|--------|---|

To constrain the search for critical stress points to a line, specify a value for two of the ordinates  $x$ ,  $y$  and  $z$ . Again, the specified ordinates will be held constant during the search. For example, if it is required to locate critical stress points on the surface of the contacting bodies along the minor axis of the contact ellipse, the following specifications would be included in the input file.

|     |                                              |   |     |   |
|-----|----------------------------------------------|---|-----|---|
| $z$ | depth below surface of body                  | = | 0.0 | m |
| $x$ | distance along major axis of contact ellipse | = | 0.0 | m |

If all three ordinates are specified, ESDUpac A0015 determines the stress at the specified single point. The following example input file fragment specifies a point located at a depth of 0.0001 m directly below the centre of the contact.

|     |                                              |   |        |   |
|-----|----------------------------------------------|---|--------|---|
| $x$ | distance along major axis of contact ellipse | = | 0.0    | m |
| $y$ | distance along minor axis of contact ellipse | = | 0.0    | m |
| $z$ | depth below surface of body                  | = | 0.0001 | m |

## 4.7 Parameters Log

ESDUpac A0015 is primarily intended to be used for tracing the contact stresses, and other selected parameters, around the circumference of a rotating cam. If such a log is required, the symbols of the parameters that are to be monitored, and the size of the cam rotational step, must be specified as shown in the following input file fragment.

|                                 |   |                |        |  |
|---------------------------------|---|----------------|--------|--|
| * Log parameters every 2 degree |   |                |        |  |
| * ~~~~~                         |   |                |        |  |
| step                            | = | 2.0            | degree |  |
| logS                            | = | phi, yM, QeMax |        |  |

In the above example, the user has specified that the cam rotational angle,  $\phi$ , the follower lift,  $yM$ , and the maximum equivalent shear stress,  $QeMax$ , be logged every 2 degree of cam rotation. Up to 10 of the parameters listed in Table 4.4 can be logged in any one run of the program.

By default, the requested parameters are logged over the full interval of cam rotation for which follower motion cam laws have been defined (see Section 4.2). If the parameters are to be logged over just a part of this interval, the starting and/or ending values of cam rotation must be specified as shown in the following input fragment.

```
* Log parameters over restricted range
* ~~~~~
phiBot = 90      degree
phiTop = 180     degree
```

By default, any parameters log produced is recorded in the auxiliary output file named "LOG.OUT". If the log is required to be recorded in an alternative file, the name of the file must be specified explicitly as shown in the following input file fragment.

```
* Record parameters log in another file
* ~~~~~
logF      name of parameters log file          = 'MYLOG.OUT'
```

A sample parameters log file is presented and described in Section 6.

**TABLE 4.4 PARAMETERS THAT CAN BE LOGGED**

| Symbol                                                                | Description                                                                                                                                                                                                                                                                                                                                                                                      | Units                                                                                                      |
|-----------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| phi<br>time                                                           | angle of cam rotation<br>elapsed time                                                                                                                                                                                                                                                                                                                                                            | degree<br>s                                                                                                |
| yM<br>yF<br>yD1Phi<br>yD2Phi<br>yD3Phi<br>y1Dot<br>y2Dot<br>y3Dot     | displacement of follower (from Xm axis)<br>displacement of follower (from Y0 datum)<br>differential of displacement with respect to cam angle<br>second differential of displacement with respect to cam angle<br>third differential of displacement with respect to cam angle<br>velocity of follower<br>acceleration of follower<br>jerk of follower                                           | m<br>m<br>m/rad<br>m/rad <sup>2</sup><br>m/rad <sup>3</sup><br>m/s<br>m/s <sup>2</sup><br>m/s <sup>3</sup> |
| psiM<br>psiF<br>pD1Phi<br>pD2Phi<br>pD3Phi<br>p1Dot<br>p2Dot<br>p3Dot | angular displacement of follower (from Xm axis)<br>angular displacement of follower (from psi0 datum)<br>differential of displacement with respect to cam angle<br>second differential of displacement with respect to cam angle<br>third differential of displacement with respect to cam angle<br>angular velocity of follower<br>angular acceleration of follower<br>angular jerk of follower | degree<br>degree<br>—<br>1/rad<br>1/rad <sup>2</sup><br>rad/s<br>rad/s <sup>2</sup><br>rad/s <sup>3</sup>  |
| Pe<br>Ps<br>Pc<br>Pn                                                  | external closure force on follower<br>spring closure force on follower<br>total closure force (Pe + Ps)<br>inertial force of follower                                                                                                                                                                                                                                                            | N<br>N<br>N<br>N                                                                                           |
| Te<br>Ts<br>Tc<br>Tn                                                  | external closure moment on follower<br>spring closure moment on follower<br>total closure moment (Te + Ts)<br>inertial moment of follower                                                                                                                                                                                                                                                        | N m<br>N m<br>N m<br>N m                                                                                   |
| omgF<br>omgR<br>omgFD<br>Nr<br>Pb<br>Pm<br>cMu                        | absolute angular velocity of follower roller<br>angular velocity of follower roller relative to follower<br>angular acceleration of follower roller<br>number of revolutions of follower roller<br>follower roller instantaneous bearing load<br>follower roller bearing mean load<br>critical value of friction coefficient                                                                     | rad/s<br>rad/s<br>rad/s <sup>2</sup><br>—<br>N<br>N<br>—                                                   |

**TABLE 4.4 PARAMETERS THAT CAN BE LOGGED (continued)**

| Symbol | Description                                                  | Units            |
|--------|--------------------------------------------------------------|------------------|
| Qc     | cam driving torque                                           | N m              |
| work   | cumulative driving work                                      | J                |
| power  | averaged driving power                                       | W                |
| xCp    | x co-ordinate of contact point in fixed axes                 | m                |
| yCp    | y co-ordinate of contact point in fixed axes                 | m                |
| xCs    | x co-ordinate of contact point in cam axes                   | m                |
| yCs    | y co-ordinate of contact point in cam axes                   | m                |
| rCp    | polar co-ordinate radius of contact point                    | m                |
| phiCp  | polar co-ordinate angle of contact in fixed axes             | degree           |
| phiCs  | polar co-ordinate angle of contact in cam axes               | degree           |
| sCf    | contact point distance on follower                           | m                |
| yDotC  | surface velocity of cam                                      | m/s              |
| yDotF  | surface velocity of follower                                 | m/s              |
| Pz     | normal contact force                                         | N                |
| Py     | tangential contact force                                     | N                |
| alpha  | pressure angle                                               | degree           |
| CxC    | cam crown curvature                                          | 1/m              |
| CyC    | cam profile curvature                                        | 1/m              |
| CxF    | follower crown curvature                                     | 1/m              |
| CyF    | follower profile curvature (dome or roller)                  | 1/m              |
| a      | major semi-axis of contact ellipse                           | m                |
| b      | minor semi-axis of contact ellipse                           | m                |
| delta  | normal approach of cam and follower                          | m                |
| Po     | maximum Hertzian pressure                                    | N/m <sup>2</sup> |
| Tmax   | maximum tensile stress                                       | N/m <sup>2</sup> |
| xTmax  | x co-ordinate of location of maximum tensile stress          | m                |
| yTmax  | y co-ordinate of location of maximum tensile stress          | m                |
| zTmax  | z co-ordinate of location of maximum tensile stress          | m                |
| QeMax  | maximum equivalent shear stress                              | N/m <sup>2</sup> |
| xQeMax | x co-ordinate of maximum equivalent shear stress             | m                |
| yQeMax | y co-ordinate of maximum equivalent shear stress             | m                |
| zQeMax | z co-ordinate of maximum equivalent shear stress             | m                |
| dQoMax | maximum change in orthogonal shear stress                    | N/m <sup>2</sup> |
| zQoMax | z co-ordinate of maximum orthogonal change                   | m                |
| fx     | direct stress component in x direction                       | N/m <sup>2</sup> |
| fy     | direct stress component in y direction                       | N/m <sup>2</sup> |
| fz     | direct stress component in z direction                       | N/m <sup>2</sup> |
| Qxy    | shear stress component in x plane, y direction               | N/m <sup>2</sup> |
| Qyz    | shear stress component in y plane, z direction               | N/m <sup>2</sup> |
| Qzx    | shear stress component in z plane, x direction               | N/m <sup>2</sup> |
| Qe     | equivalent shear stress                                      | N/m <sup>2</sup> |
| uEntr  | lubricant entrainment velocity                               | m/s              |
| hMin   | minimum lubricant film thickness (see Derivations 17 and 18) | m                |
| lambda | specific film thickness                                      | —                |
| Tf     | Blok flash temperature rise (see Derivation 19)              | K                |

Note that the running time of the program increases with the smallness of the rotational step and the number and type of the parameters logged. Very briefly, motion parameters, such as follower displacement, velocity and acceleration, and follower external loads are the least computationally expensive while stress parameters are the most expensive.

This page Amendment A

## 4.8 Stress Distributions

ESDUpac A0015 is primarily intended to be used for tracing the variation of contact stresses, and other selected parameters, around the circumference of a rotating cam as described in Section 4.7. If it is required to examine parts of the cycle in more detail, however, stress distribution tables suitable for plotting can be produced for a single instantaneous value of cam rotation. If such stress distribution tables are required, the instantaneous value of cam rotation,  $\phi$ , must be specified as shown in the following input file fragment.

```
* Examine the 125 degree point in more detail
* ~~~~~
phi      instantaneous cam rotation      = 125.0      degree
```

By default, any stress distribution tables produced are recorded in the auxiliary output file named "STRESS.OUT". If the tables are required to be recorded in an alternative file, the name of the file must be specified explicitly as shown in the following input file fragment.

```
* Record stress distributions in another file
* ~~~~~
disF     name of stress distributions file      = 'TABLES.OUT'
```

The types of stress distributions contained in the file depends on the constraints that have been placed on the calculations (see Section 4.6). Briefly, if no constraints have been placed on the calculations (*i.e.* none of the ordinates  $x$ ,  $y$  or  $z$  have been assigned a value in the input file), the stress distributions file will contain values of surface stress around the perimeter of the contact and values of the maximum stresses at various depths. If a single constraint has been placed on the calculations (*i.e.* one of the ordinates  $x$ ,  $y$  or  $z$  has been assigned a value in the input file), the stress distributions file will contain stress values over a cross-section. If values have been assigned to two of the ordinates  $x$ ,  $y$  or  $z$ , the stress distributions file will contain stress values along a line. The content of the stress distributions file is described in more detail in Section 7.

The extent of the stress distributions generated can be controlled by the parameters  $xBot$ ,  $xTop$ ,  $yBot$ ,  $yTop$ ,  $zBot$  and  $zTop$  although normally these parameters will not need to be specified. By default all stress distributions (except those around the perimeter of the contact area) are confined to a cuboidal volume extending 1.5 times the contact ellipse axis dimensions in the horizontal ( $x$  and  $y$ ) directions and twice the contact ellipse semi-minor axis dimension into the depth of the body. This volume is sufficiently large to encompass all positions of interest in the majority of situations. If required, however, the extent and position of this volume can be changed, for example to examine a small region, as can the number of stress values that are calculated for the stress distributions. The following example specifications, added to the input file, redefine the horizontal ( $x$  and  $y$ ) extent of the volume (see also Example 3 of Derivation 4).

```
xBot  lower limit on x for stress distributions = 0.001    m
xTop  upper limit on x for stress distributions = 0.0015   m

yBot  lower limit on y for stress distributions = 0.0       m
yTop  upper limit on y for stress distributions = 0.0002    m
```

If required, the upper and lower limits in the  $z$  direction,  $zBot$  and  $zTop$ , could be similarly redefined. Redefining the extent of the volume in this manner might be used to examine in more detail selected areas after first obtaining stress distributions for the original default volume. In this way the dimensions of the contact area will have been established before the region of interest is specified for detailed analysis.

By default, all intervals over which the stress distributions are obtained are divided into 30 equal sized steps. Thus, for a distribution over a cross-section, stress values would be calculated at 31 by 31 points. To increase the number of steps to 50, say, include the following specification in the input file.

```
nGrid    number of steps for stress distributions    =    50
```

Note that increasing the number of steps, `nGrid`, will result in increased program running time and a larger stress distributions file (see Section 7). The default value of 30 is likely to be sufficient when it is required to plot the variation of stress with a single ordinate only. The value might need to be increased when it is intended to plot contours, for example, of a particular stress component over a cross-section. Note that the size of the stress distributions file, and the running time of the program, can be reduced by selecting only those stress components which are of interest. For example, to select just the direct stress component, `fz`, and the equivalent stress, `Qe`, the following specification would be added to the input file.

```
disS      =    fz    Qe
```

The components that can be selected in this manner are listed in Table 4.5

| TABLE 4.5 STRESS COMPONENTS FOR DISTRIBUTIONS FILE |                                                |                  |
|----------------------------------------------------|------------------------------------------------|------------------|
| Symbol                                             | Description                                    | Units            |
| Tmax                                               | maximum tensile stress                         | N/m <sup>2</sup> |
| Qe                                                 | equivalent shear stress                        | N/m <sup>2</sup> |
| Qo                                                 | orthogonal shear stress                        | N/m <sup>2</sup> |
| fx                                                 | direct stress component in x direction         | N/m <sup>2</sup> |
| fy                                                 | direct stress component in y direction         | N/m <sup>2</sup> |
| fz                                                 | direct stress component in z direction         | N/m <sup>2</sup> |
| Qxy                                                | shear stress component in x plane, y direction | N/m <sup>2</sup> |
| Qyz                                                | shear stress component in y plane, z direction | N/m <sup>2</sup> |
| Qzx                                                | shear stress component in z plane, x direction | N/m <sup>2</sup> |

By default, ESDUpac A0015 includes all relevant stress components in any stress distributions file produced (see Section 7).

## 4.9 Summary of Input Parameters

Table 4.6 describes all the input parameters and indicates the allowable values and, where applicable, the default values. Only a subset of the parameters might be used in any one input file. More detailed descriptions for the input parameters are given in Appendix B together with comments on their purpose and specification. The program issues error messages stating the valid range if any of the specified input parameters are invalid. Further validation checks are applied to many of the input parameters in combination. For example, error messages are issued if insufficient information has been provided to define the properties of the follower or to define a particular cam law portion. All potential error and warning messages are described in Appendix C.

**TABLE 4.6 DESCRIPTION OF INPUT PARAMETERS**

| Symbol | Description                                  | Allowable values                                           | Default (if any)                   |
|--------|----------------------------------------------|------------------------------------------------------------|------------------------------------|
| omega  | cam rotational velocity                      | $\pm$ (0.01 to 1000.0) rev/s                               | –                                  |
| lawDB  | name of cam laws database                    | valid file name/path (128 characters max.)                 | CAMLAWS.DAT                        |
| Rise   | cam law name for a rise portion              | alphanumeric name (32 characters max.)                     | –                                  |
| Return | cam law name for a return portion            | alphanumeric name (32 characters max.)                     | –                                  |
| Dwell  | signifies a dwell portion                    | any                                                        | –                                  |
| phiP   | angular extent of a cam portion              | 0.0 to 360.0 degree                                        | –                                  |
| hP     | translating follower portion movement        | 0.0 to 1.0 m                                               | –                                  |
| psiP   | swinging follower portion movement           | 0.0 to 180.0 degree                                        | –                                  |
| u0     | normalised input at start of cam portion     | 0.0 to 1.0                                                 | 1.0                                |
| u1     | normalised input at end of cam portion       | 0.0 to 1.0                                                 | 1.0                                |
| motF   | name of motion file                          | valid file name/path (128 characters max.)                 | –                                  |
| loadDB | name of external loads database              | valid file name/path (128 characters max.)                 | EXLOADS.DAT                        |
| load   | load expressions block name                  | alphanumeric name (32 characters max.)                     | –                                  |
| fol    | follower type                                | TFlat, TDome, TRoll, SFlat, SDome or SRoll                 | –                                  |
| Rc     | crown radius of follower                     | 0.001 to (infinite) m                                      | –                                  |
| Rf     | roller or dome radius                        | 0.001 to 1.0 m                                             | –                                  |
| E      | translating follower offset                  | -1.0 to 1.0 m                                              | –                                  |
| alpT   | translating follower face angle              | -45.0 to 45.0 degree                                       | –                                  |
| mFol   | translating follower mass                    | $1.0 \times 10^{-3}$ to $1.0 \times 10^3$ kg               | –                                  |
| Y0     | translating follower motion datum            | 0.0 to 1.0 m                                               | –                                  |
| Psp    | compression spring preload force             | 0.0 to $10.0 \times 10^3$ N                                | 0.0                                |
| kSc    | compression spring stiffness                 | 0.0 to $1.0 \times 10^6$ N/m                               | 0.0                                |
| D      | cam centre/follower pivot distance           | 0.001 to 1.0 m                                             | –                                  |
| C      | swinging follower arm crank length           | -1.0 to 1.0 m                                              | –                                  |
| L      | swinging follower pivot/dome centre distance | 0.001 to 1.0 m                                             | –                                  |
| Ifol   | swinging follower mass moment of inertia     | 0.001 to 100.0 kg m <sup>2</sup>                           | –                                  |
| Irol   | follower roller mass moment of inertia       | 0.0 to $1.0 \times 10^{-3}$ kg m <sup>2</sup>              | 0.0                                |
| psi0   | swinging follower motion datum               | 0.0 to 180.0 degree                                        | –                                  |
| Tsp    | torsion spring preload moment                | 0.0 to $10.0 \times 10^3$ N m                              | 0.0                                |
| kSt    | torsion spring stiffness                     | 0.0 to $1.0 \times 10^6$ N m/rad                           | 0.0                                |
| wf     | width of cam/follower face                   | 0.001 to 1.0 m                                             | 1.0 m                              |
| body   | body of interest                             | Cam or Follower                                            | Cam                                |
| Ec     | elastic modulus of cam material              | $1.0 \times 10^6$ to $1.0 \times 10^{12}$ N/m <sup>2</sup> | $210 \times 10^9$ N/m <sup>2</sup> |
| sigC   | Poisson's ratio of cam material              | 0.0 to 0.9                                                 | 0.3                                |
| Ef     | elastic modulus of follower material         | $1.0 \times 10^6$ to $1.0 \times 10^{12}$ N/m <sup>2</sup> | $210 \times 10^9$ N/m <sup>2</sup> |
| sigF   | Poisson's ratio of follower material         | 0.0 to 0.9                                                 | 0.3                                |
| rMu    | coefficient of kinetic friction              | 0.0 to 1.0                                                 | 0.0                                |
| logF   | name of parameters log file                  | valid file name/path (128 characters max.)                 | LOG.OUT                            |
| logS   | list of symbols of parameters to log         | comma delimited list of symbols                            | blank                              |
| step   | cam rotation step size                       | 0.001 to 10.0 degree                                       | –                                  |
| phiBot | starting cam angle for logging of parameters | 0.0 to 360.0 degree                                        | start of portions                  |
| phiTop | ending cam angle for logging of parameters   | 0.0 to 360.0 degree                                        | end of portions                    |
| x      | major axis ordinate constraint position      | -1.0 to 1.0 m                                              | –                                  |
| y      | minor axis ordinate constraint position      | -1.0 to 1.0 m                                              | –                                  |
| z      | depth axis ordinate constraint position      | 0.0 to 1.0 m                                               | –                                  |

| disF<br>disS | name of stress distributions file<br>list of symbols of stresses for distributions | valid file name/path (128 characters max.)<br>comma delimited list of symbols |    |                       |                    | STRESS.OUT<br>all stresses               |
|--------------|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|----|-----------------------|--------------------|------------------------------------------|
| phi          | cam angle from start of rotation                                                   | 0.0                                                                           | to | 360.0                 | degree             | –                                        |
| nGrid        | number of steps for stress distributions                                           | 10                                                                            | to | 100                   |                    | 30                                       |
| xBot         | lower constraint on x for stress distribution                                      | -1.0                                                                          | to | 1.0                   | m                  | -1.5a                                    |
| xTop         | upper constraint on x for stress distribution                                      | -1.0                                                                          | to | 1.0                   | m                  | 1.5a                                     |
| yBot         | lower constraint on y for stress distribution                                      | -1.0                                                                          | to | 1.0                   | m                  | -1.5b                                    |
| yTop         | upper constraint on y for stress distribution                                      | -1.0                                                                          | to | 1.0                   | m                  | 1.5b                                     |
| zBot         | lower constraint on z for stress distribution                                      | 0.0                                                                           | to | 1.0                   | m                  | 0.0                                      |
| zTop         | upper constraint on z for stress distribution                                      | 0.0                                                                           | to | 1.0                   | m                  | 2.0b                                     |
| eta0         | lubricant dynamic viscosity                                                        | $0.1 \times 10^{-3}$                                                          | to | 10.0                  | N s/m <sup>2</sup> | $30.0 \times 10^{-3}$ N s/m <sup>2</sup> |
| alp0         | pressure exponent of lubricant viscosity                                           | 0.0                                                                           | to | $50.0 \times 10^{-9}$ | m <sup>2</sup> /N  | $25.0 \times 10^{-9}$ m <sup>2</sup> /N  |
| RqC          | RMS roughness of cam surface                                                       | $0.01 \times 10^{-6}$                                                         | to | $10.0 \times 10^{-6}$ | m                  | $1.0 \times 10^{-6}$ m                   |
| RqF          | RMS roughness of follower surface                                                  | $0.01 \times 10^{-6}$                                                         | to | $10.0 \times 10^{-6}$ | m                  | $1.0 \times 10^{-6}$ m                   |
| rhoCc        | volumetric heat capacity of cam material                                           | $0.1 \times 10^6$                                                             | to | $20.0 \times 10^6$    | J/m <sup>3</sup> K | $3.5 \times 10^6$ J/m <sup>3</sup> K     |
| rhoCf        | volumetric heat capacity of follower material                                      | $0.1 \times 10^6$                                                             | to | $20.0 \times 10^6$    | J/m <sup>3</sup> K | $3.5 \times 10^6$ J/m <sup>3</sup> K     |
| kC           | thermal conductivity of cam material                                               | 0.01                                                                          | to | 200.0                 | W/m K              | 30.0 W/m K                               |
| kF           | thermal conductivity of follower material                                          | 0.01                                                                          | to | 200.0                 | W/m K              | 30.0 W/m K                               |

## 5. THE OUTPUT DATA FILE

The output data file includes the results of the analysis carried out by the ESDUpac program. The file can be examined using an ASCII text editor. An example output data file is shown here.

```

-----
ESDU International plc.

ESDUpac Number:  A0015
ESDUpac Title:   Disc cams: tribological analysis
Data Item Number: 00015
Data Item Title:  Disc cams: tribological analysis
                  using computer program A0015
ESDUpac Version:  1.0, May 2000.
-----

Name of input data file
C:\ESDU\A0015\EG1.IN

INPUT DATA
~~~~~

* Follower specification
* ~~~~~
fol      follower type          = TDome

E        follower offset        = 0.01  m
Rf       follower dome radius   = 0.05  m
Rc       follower crown radius  = 0.5   m

mFol     follower mass          = 0.5   kg

Y0       follower motion datum  = 0.1   m
Psp      follower spring preload = 50    N

* Follower motion specification
* ~~~~~
omega    cam rotational speed   = 10    rev/s

Dwell    dwell cam portion      = Dwell
phiP     extent of portion      = 45    degree

Rise     rise cam portion       = ModTrap
phiP     extent of portion      = 90    degree
hP       movement of portion    = 0.01  m

Dwell    dwell cam portion      = Dwell
phiP     extent of portion      = 45    degree

Return   return cam portion     = ModTrap
phiP     extent of portion      = 180   degree
hP       movement of portion    = 0.01  m

* Parameters log
* ~~~~~
logS     logged parameters      = phi, QeMax
step     cam rotational step    = 1.0   degree

```

## OUTPUT DATA

### CAM FOLLOWER

fol follower type = translating domed

E follower offset ..... = 10.0 E-03 m  
 Rf dome radius ..... = 50.0 E-03 m  
 Rc crown radius of dome ..... = 0.500 m  
 mFol follower mass ..... = 0.500 kg  
 wF width of cam/follower face ..... = 1.00 m  
  
 Psp return spring preload force ..... = 50.0 N  
 kSc return spring stiffness..... = 0.00 N/m

### EXTERNAL LOADS

There are no additional external loads

### CAM AND FOLLOWER MATERIALS

Ec elastic modulus of cam material ..... = 0.210 E+12 N/m<sup>2</sup>  
 Ef elastic modulus of follower material ..... = 0.210 E+12 N/m<sup>2</sup>  
 sigC Poisson's ratio of cam material ..... = 0.300  
 sigF Poisson's ratio of follower material ..... = 0.300  
  
 rMu coefficient of kinetic friction ..... = 0.00

### CAM FOLLOWER MOTION

lawDB cam laws database = CAMLAWS.DAT

| Portion type and law used: |          | Extent:         | Movement: | Normalised extent: |      |
|----------------------------|----------|-----------------|-----------|--------------------|------|
| Type                       | Law name | phiP,<br>degree | hP,<br>m  | u0                 | u1   |
| Dwell                      | Dwell    | 45.0            | 0.00      | 0.00               | 1.00 |
| Rise                       | ModTrap  | 90.0            | 10.0 E-03 | 0.00               | 1.00 |
| Dwell                      | Dwell    | 45.0            | 0.00      | 0.00               | 1.00 |
| Return                     | ModTrap  | 0.180 E+03      | 10.0 E-03 | 0.00               | 1.00 |

omega rotational velocity of cam ..... = 10.0 rev/s

Y0 follower displacement datum ..... = 0.100 m  
 Ht total follower movement ..... = 10.0 E-03 m  
 phiT total angular extent ..... = 0.360 E+03 degree

### LOG OUTPUT FILE

logF log file name = LOG.OUT  
 logS logged parameters = phi, QeMax  
 step cam rotation step = 1.00 degree

\*\*\*Normal end

The output file is arranged into three major sections. The first section provides an exact copy of the input data from the corresponding input file. The second section provides a summary of those input data together with any default values assumed by the program. The final section includes the results of the computations performed by the program or indicates where those results can be found.

The above example output file contains little, if any, actual computed data since these are in the log file mentioned in the last section headed "LOG OUTPUT FILE" (see Section 6). Parameters are only logged if the angular interval of cam rotation, or step size, between consecutive values has been specified in the input file (see Section 4.7). If instead, a particular value of cam rotation,  $\phi_i$ , is specified in the input data (see Section 4.8), a more comprehensive output data file is produced as shown here.

```

-----
ESDU International plc.

ESDUpac Number:   A0015
ESDUpac Title:    Disc cams: tribological analysis
Data Item Number: 00015
Data Item Title:   Disc cams: tribological analysis
                  using computer program A0015
ESDUpac Version:  1.0, May 2000.
-----
Name of input data file
C:\ESDU\A0015\EG7.IN

INPUT DATA
~~~~~

* Follower specification
* ~~~~~
fol      follower type          = TDome

E        follower offset        = 0.01   m
Rf       follower dome radius   = 0.05   m
Rc       follower crown radius  = 0.5    m

mFol     follower mass          = 0.5    kg
Psp      follower spring preload = 50     N

Y0       follower motion datum  = 0.1    m

* Follower motion specification
* ~~~~~
omega    cam rotational speed   = 10     rev/s

Dwell    dwell cam portion      = Dwell
phiP     extent of portion      = 90     degree

Rise     rise cam portion       = ModTrap
phiP     extent of portion      = 90     degree
hP       lift of portion        = 0.01   m

Return   return cam portion     = ModTrap
phiP     extent of portion      = 180    degree
hP       lift of portion        = 0.01   m

* Cam and follower materials
* ~~~~~
Ec       elastic modulus of cam  = 1E12   N/m^2
Ef       elastic modulus of follower = 1E12   N/m^2

```

\* Cam position

\* ~~~~~

phi instantaneous cam rotation = 150 degree

## OUTPUT DATA

~~~~~

## CAM FOLLOWER

~~~~~

fol follower type = translating domed

E follower offset ..... = 10.0 E-03 m  
 Rf dome radius ..... = 50.0 E-03 m  
 Rc crown radius of dome ..... = 0.500 m  
 mFol follower mass ..... = 0.500 kg  
 wF width of cam/follower face ..... = 1.00 m

Psp return spring preload force ..... = 50.0 N  
 kSc return spring stiffness..... = 0.00 N/m

## EXTERNAL LOADS

~~~~~

There are no additional external loads

## CAM AND FOLLOWER MATERIALS

~~~~~

Ec elastic modulus of cam material ..... = 1.00 E+12 N/m^2  
 Ef elastic modulus of follower material ..... = 1.00 E+12 N/m^2  
 sigC Poisson's ratio of cam material ..... = 0.300  
 sigF Poisson's ratio of follower material ..... = 0.300  
 rMu coefficient of kinetic friction ..... = 0.00

## CAM FOLLOWER MOTION

~~~~~

lawDB cam laws database = CAMLAWS.DAT

| Portion type and law used: |          | Extent:         | Movement: | Normalised extent: |      |
|----------------------------|----------|-----------------|-----------|--------------------|------|
| Type                       | Law name | phiP,<br>degree | hP,<br>m  | u0                 | u1   |
| Dwell                      | Dwell    | 90.0            | 0.00      | 0.00               | 1.00 |
| Rise                       | ModTrap  | 90.0            | 10.0 E-03 | 0.00               | 1.00 |
| Return                     | ModTrap  | 0.180 E+03      | 10.0 E-03 | 0.00               | 1.00 |

omega rotational velocity of cam ..... = 10.0 rev/s

Y0 follower displacement datum ..... = 0.100 m  
 Ht total follower movement ..... = 10.0 E-03 m  
 phiT total angular extent ..... = 0.360 E+03 degree

## CAM/FOLLOWER CONTACT

~~~~~

phi instantaneous angular position of cam ..... = 0.150 E+03 degree

## Contact Dimensions (elliptical)

~~~~~

a major semi-axis of contact ellipse ..... = 0.284 E-03 m  
 b minor semi-axis of contact ellipse ..... = 38.4 E-06 m  
 delta normal approach of cam and follower ..... = 0.111 E-06 m

```

Contact Loading
~~~~~
Pz    normal load on contact ..... = 10.9      N
Py    frictional shear load on contact ..... = 0.00      N
Po    maximum Hertzian pressure ..... = 0.476 E+09 N/m^2

Contact Stresses (Cam)
~~~~~
Global maxima:

QeMax  maximum value of equivalent stress      = 0.159 E+09 N/m^2
       located at                               x = 1.94 E-09 m
                                              y = 0.00      m
                                              z = 27.5 E-06 m

Tmax   maximum value of tensile stress          = 45.0 E+06 N/m^2
       located at                               x = 0.284 E-03 m
                                              y = 0.506 E-09 m
                                              z = 0.00      m

dQoMax maximum change in orthogonal shear      = 0.237 E+09 N/m^2
       located at a depth of                     z = 19.0 E-06 m

STRESS OUTPUT FILE
~~~~~
disF   stress file name = STRESS.OUT
disS   stresses requested = Tmax,Qe,Qo,fx,fy,fz,Qxy,Qyz,Qzx

The stress distributions file contains:
  A list of values of Tmax around contact perimeter
  A list of values of Qe around contact perimeter
  A list of values of QeMax at various depths
  A list of values of dQoMax at various depths

-----
***Normal end

```

In this alternative output file, the "LOG OUTPUT FILE" section has been replaced by the sections headed "CAM/FOLLOWER CONTACT" and "STRESS OUTPUT FILE" which together summarise the results of the computations for the single rotational position of the cam. The content of the stress output file is described in Section 7.

With both forms of output file, a further section entitled "ERROR/WARNING MESSAGES" is included if the input data have been found to be invalid or if the computations have been aborted. An example of such a section is shown here.

```

ERROR/WARNING MESSAGES
~~~~~
ERROR CF39. The follower has lost contact with the cam surface

```

All ESDUpac programs in the Tribology Series incorporate comprehensive data validation. Input data are checked against both static validation limits applied to each individual input parameter and computed validation limits applied to combinations of input parameters. Further validation is applied in the course of computing the output data. The validation error messages and warning messages that might be issued by this particular ESDUpac program are listed in Appendix C along with a brief discussion of the possible causes of each message being issued and, where applicable, the remedial action to be taken.