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Blending profiles of disc cams with radial translating roller followers. Part 1: to reduce segment angle, reduce reference circle radius or increase follower lift

**Associated software: ESDUpac A9214
VIEWpac 9214A**

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The Mechanisms Committee, which first met in 1975, is continuing the work that previously was the responsibility of the former Gearing and Mechanisms Committee, which first met in November 1964. Like the earlier Committee it has the co-operation of many engineers and scientists in industry, research establishments and universities from whom much assistance and information is being received.

BLENDING PROFILES OF DISC CAMS WITH RADIAL TRANSLATING ROLLER FOLLOWERS. PART 1: to reduce segment angle, reduce reference circle radius or increase follower lift

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BLENDING PROFILES OF DISC CAMS WITH RADIAL TRANSLATING ROLLER FOLLOWERS. Part 1: to reduce segment angle, reduce reference circle radius or increase follower lift

1. NOTATION

The units used in this Item are predominantly SI but any coherent system of units may be used. All angles are measured positively in an anticlockwise sense and the cam is considered to rotate in an anticlockwise direction

		Units
H	total follower lift corresponding to one segment	m
k_B	blending ratio	—
O	cam centre of rotation and origin of co-ordinate axis system	—
R_a	prime circle radius	m
R_b	reference circle radius	m
R_g	cutter (or grinder) radius	m
R_r	roller radius	m
u	normalised cam angle	—
w	normalised follower displacement	—
w'	non-dimensional follower velocity	—
w''	non-dimensional follower acceleration	—
X_c, Y_c	axes fixed in, and rotating with, cam with origin at point O	—
X_m, Y_m	axes fixed in machine, with origin at point O	—
y	translational displacement of follower	m
$\dot{y}$	translational velocity of follower	m/s
$\ddot{y}$	translational acceleration of follower	m/s ²
y_m	instantaneous height of centre of roller above X_m -axis	m
y_0	height of centre of roller above X_m -axis at inner dwell of segment	m
Z	intermediate calculation parameter (see Equation (3.18))	—

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α	pressure angle	degree
ρ	radius of curvature of pitch curve	m
ρ_p	radius of curvature of cam profile	m
Φ	total angle of cam rotation corresponding to one segment	degree
ϕ	intermediate angle of cam rotation from inner dwell	degree
ϕ_0	angle of cam rotation at inner dwell	degree
ω_c	angular velocity of cam	rad/s

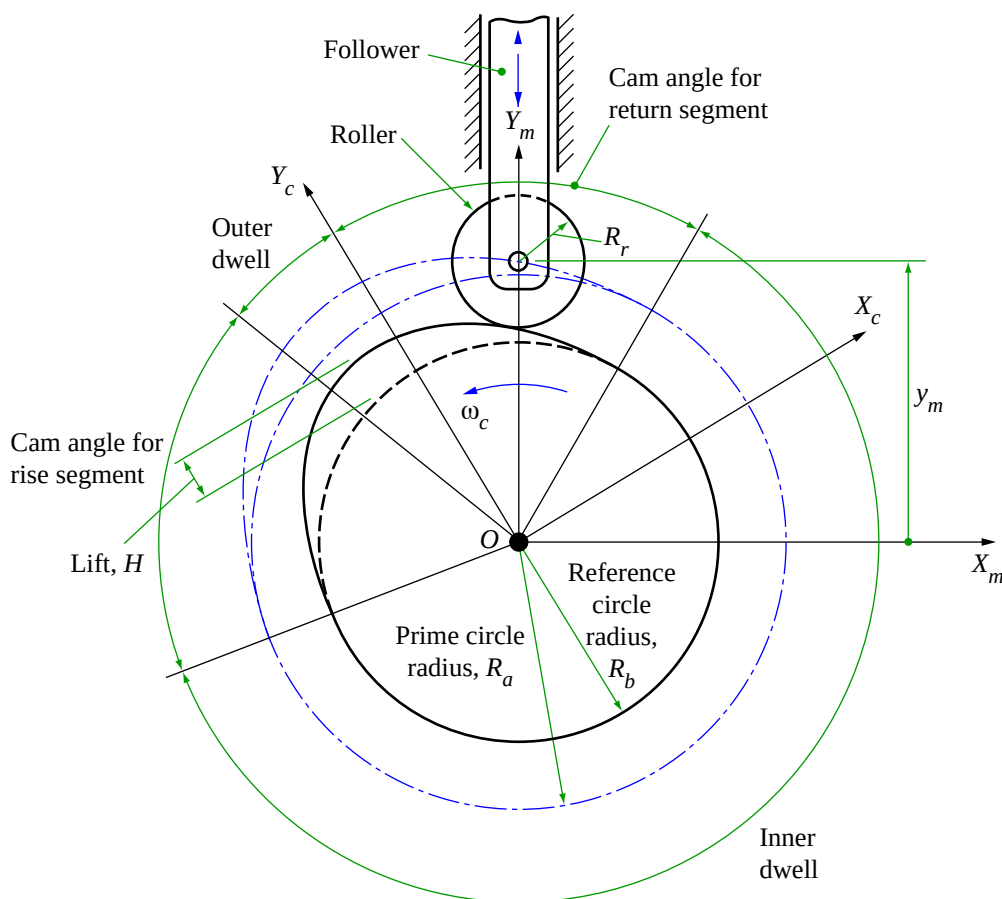
Subscripts

B	refers to blended segment
max	indicates maximum magnitude
min	indicates minimum magnitude
$N1$	refers to notional dimension of inner component
$N2$	refers to notional dimension of outer component
S	refers to single-law (unblended) motion
$V1$	refers to normalised location of maximum follower velocity (w.r.t. inner component)
$V2$	refers to normalised location of maximum follower velocity (w.r.t. outer component)

2. INTRODUCTION

This Data Item presents procedures for designing blended cam profiles to give reduced segment angle, reduced reference circle radius or increased follower lift in comparison with the corresponding unblended profiles. The blended segments are formed by combining portions of commonly-used cam laws such that there is continuity of follower displacement, velocity and acceleration. The procedures are applicable only to cams that drive a radial translating roller follower (see Sketch 2.1).

The proposed methods may be implemented by hand, using design data contained in ESDU 92005 (Reference 7), but it is recommended that the calculations are carried out using the computer program (ESDUpac A9214) supplied with this Item, which can cover a wider range of possible designs. The program includes checks to ensure that the pressure angle of the resultant blended profile does not exceed a specified maximum value and that profile curvature is adequate for correct action of both the roller follower and the cutter used to manufacture the cam. The program also calculates the follower motion (displacement, velocity, acceleration and jerk) throughout the segment at intervals of one degree of cam rotation.



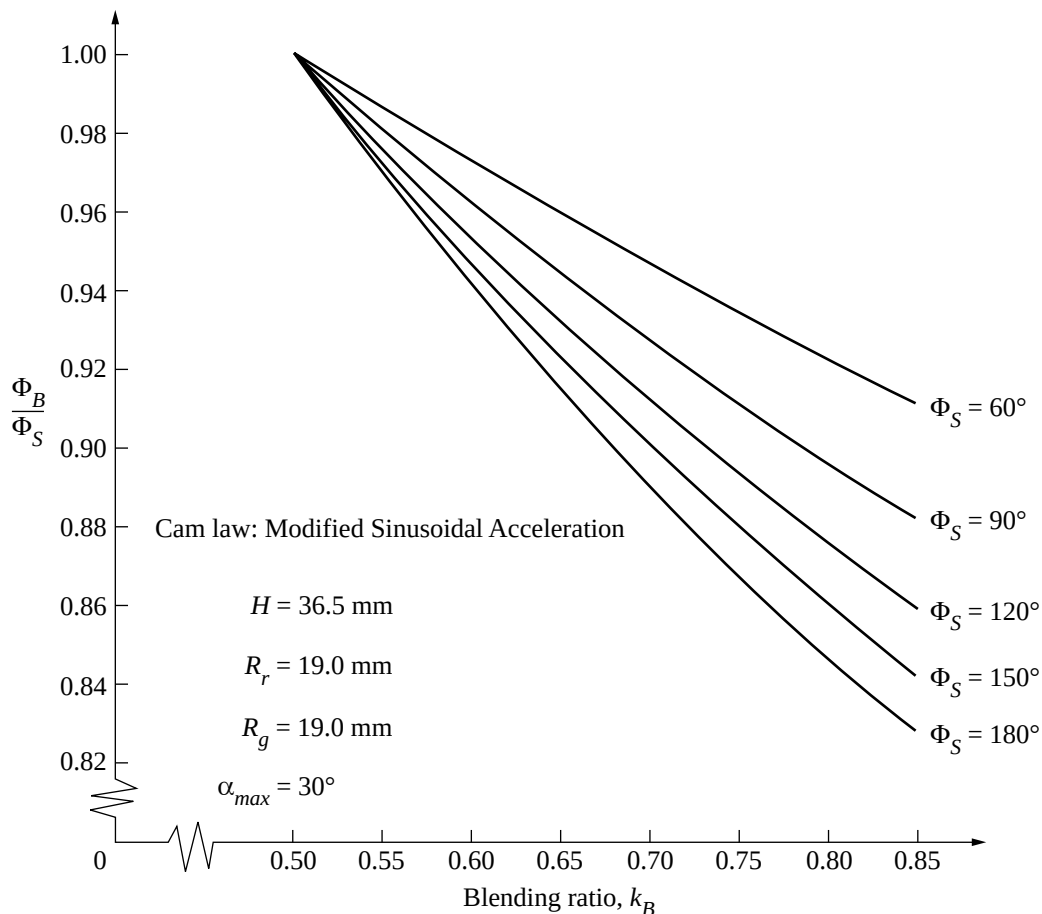
Sketch 2.1 Disc cam driving radial translating roller follower

Each procedure involves setting values of maximum allowable pressure angle, roller diameter, blending ratio and any two of the following parameters: the segment angle, the reference circle radius and the follower lift. The optimum value of the third parameter is then found (minimum allowable segment angle, minimum allowable reference circle radius or maximum allowable follower lift). These optimum values often represent significant improvements over the corresponding values associated with comparable cam profiles formed from single cam laws. Sketch 2.2 illustrates the typical benefits that can be obtained by blending a

motion segment to achieve a reduction in segment angle. The ratio of the blended profile segment angle, Φ_B , to that of a unblended single-law motion, Φ_S , is plotted against the blending ratio, k_B , for a range of values of Φ_S .

The benefits increase with blending ratio and with unblended segment angle. However the advantages can only be realised at the expense of a decreased minimum radius of curvature of the convex cam profile and increased peak follower acceleration away from the cam. These undesirable effects lead to the requirement for a more highly rated spring to maintain contact between cam and roller and consequently to increased values of contact stress at the cam/roller interface during part of the motion cycle. This can result in accelerated wear and increased risk of cam surface fatigue failure.

ESDU 83027 (see Reference 5) presents an alternative blending method based on hand calculations using a blend factor and is applicable to cams driving translating or swinging followers. A number of examples are included. The computer-based methods given in this Data Item are complementary to those shown in ESDU 83027 but are solely applicable to radial translating roller followers.



Sketch 2.2 Typical benefits obtained by blending

2.1 Reasons for Blending

Blending a cam profile using this Item involves additional design effort and so is recommended when the use of a single-law motion segment does not lead to satisfactory cam dimensions or when timing problems are encountered. Minimising the segment angle required for the follower to reach a given lift while not

increasing cam size or maximum pressure angle is a commonly encountered objective during design and severe timing problems may be alleviated using this technique. Similarly, increasing the follower lift while not changing reference circle radius, maximum pressure angle or segment angle is sometimes useful. When either the space occupied by the mechanism or the mass of moving parts is to be minimised it could be advantageous to reduce the reference circle radius of the cam. This can be achieved by blending without changing the segment angle, follower lift or maximum pressure angle. If certain conditions are met (see Section 3.1.1 and Example 2) the procedures given in this Item may be used to design advantageous DRRD motions in which the follower acceleration is not zero at the displacement reversal point.

It may also be advantageous to blend cam profiles for the following reasons (not dealt with directly in this Item).

- (a) An asymmetric motion segment may be necessary to reduce the peak follower acceleration towards the cam and hence to reduce the spring force required to maintain contact. In this case the cam must have a larger reference circle radius than that required for the corresponding symmetrical motion.
- (b) A period of constant velocity may be required before a rise segment or between two components of a rise or return motion (see ESDU 93002, Reference 9).
- (c) The follower may be required to pass through an intermediate displacement (or velocity) precision point (see ESDU 93002, Reference 9).

2.2 Use of this Data Item

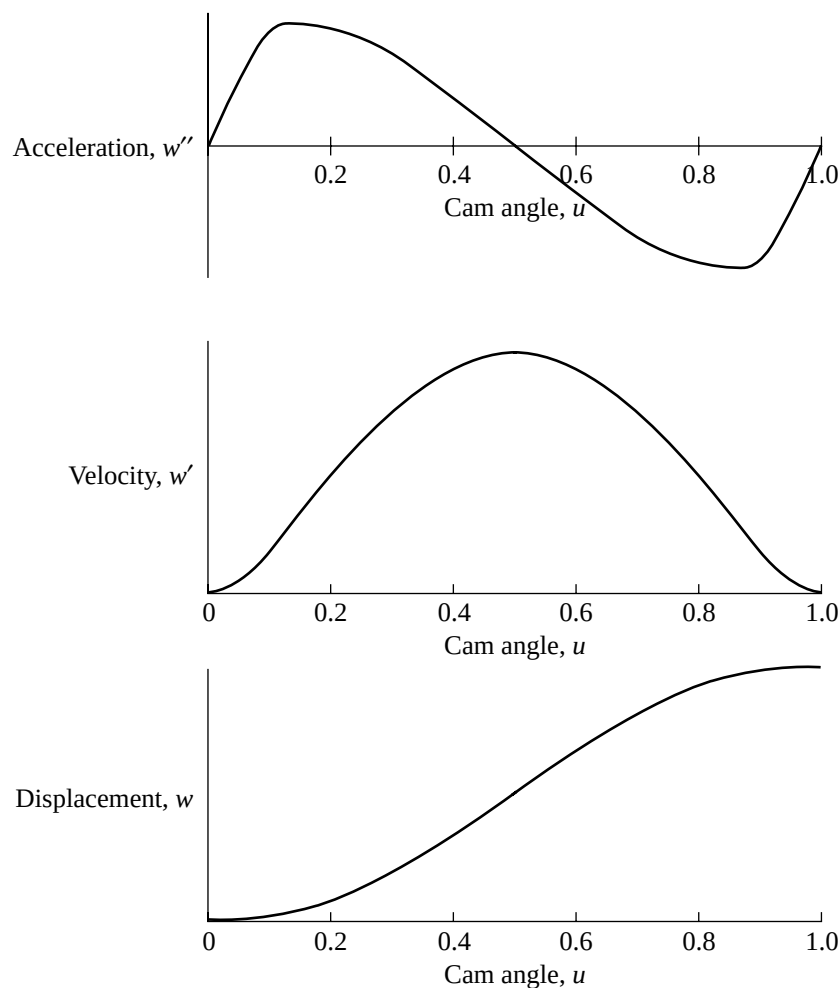
The theoretical background to blending methods, including definitions and terminology, is explained in Section 3. Calculation procedures are described in Section 4 and their use is illustrated by a series of examples in Section 7. It is strongly recommended that the calculations are performed using the computer program (ESDUpac A9214) supplied with this Item. See Section 5 for information regarding the use of this program (including construction of program input, interpretation of the program output and guidance on the design of blended profiles).

3. THEORETICAL BACKGROUND

3.1 Definitions and Terminology

3.1.1 Motion segments and single-law motion

For the purposes of this Data Item a motion segment is defined as that part of the cam motion cycle during which the follower moves from a period of zero velocity (possibly a dwell) to another period of zero velocity. A motion segment may be described as dwell-rise-dwell, dwell-return-dwell (DRD) or dwell-rise-return-dwell (DRRD). A DRRD motion segment can only be dealt with directly, using this Item, if it can be treated as two DRD motion segments joined together such that there is continuity of follower displacement, velocity and acceleration. The most common way to specify follower motion, and hence determine the cam profile, during rise or return motion is to use one of a recommended series of equations, known as cam laws, relating cam angle of rotation to follower motion (see Reference 4). To define a single-law DRD motion segment, that is, one governed by a single cam law, it is only necessary to specify the cam law, the total follower lift and the total segment angle. A typical non-dimensional follower motion (displacement, velocity and acceleration) corresponding to a symmetrical single-law motion segment is shown in Sketch 3.1.



Sketch 3.1 Non-dimensional follower motion for a typical single-law DRD segment

3.1.2 Dimensionless form of displacement, velocity and acceleration

Sketch 2.1 shows two pairs of co-ordinate axes having origins coincident with the centre of cam rotation. The X_m -, Y_m -axes are fixed to the machine frame whilst the X_c -, Y_c -axes are fixed to the cam and rotate with it. This Item is concerned only with the common case in which the follower path coincides with the Y_m -axis (i.e. there is no offset).

A cam law is the mathematical function defining the normalised follower displacement, w , during a single motion segment in terms of normalised cam rotation, u . It is conveniently expressed as

$$w = f(u). \quad (3.1)$$

This function is evaluated readily by substituting the equation for the relevant cam law. In this Item the cam laws are identified by their generic names, for example Cycloidal or Modified Sinusoidal Acceleration. The equations of motion for commonly-used cam laws are given as formulae and graphically in ESDU 82006 (see Reference 4). For a disc cam driving a radial translating follower (see Sketch 2.1), the normalised cam rotation and normalised follower displacement for each motion segment are given by

$$u = (\phi - \phi_0)/\Phi \quad (3.2)$$

$$\text{and} \quad w = (y_m - y_0)/H. \quad (3.3)$$

Making the usual assumption that the cam rotates at constant angular velocity, the dimensionless forms of the follower velocity and acceleration are defined as

$$w' = \frac{\dot{y}}{\omega_c H} \left\{ \frac{\pi \Phi}{180} \right\} \quad (3.4)$$

$$\text{and} \quad w'' = \frac{\ddot{y}}{\omega_c^2 H} \left\{ \frac{\pi \Phi}{180} \right\}^2. \quad (3.5)$$

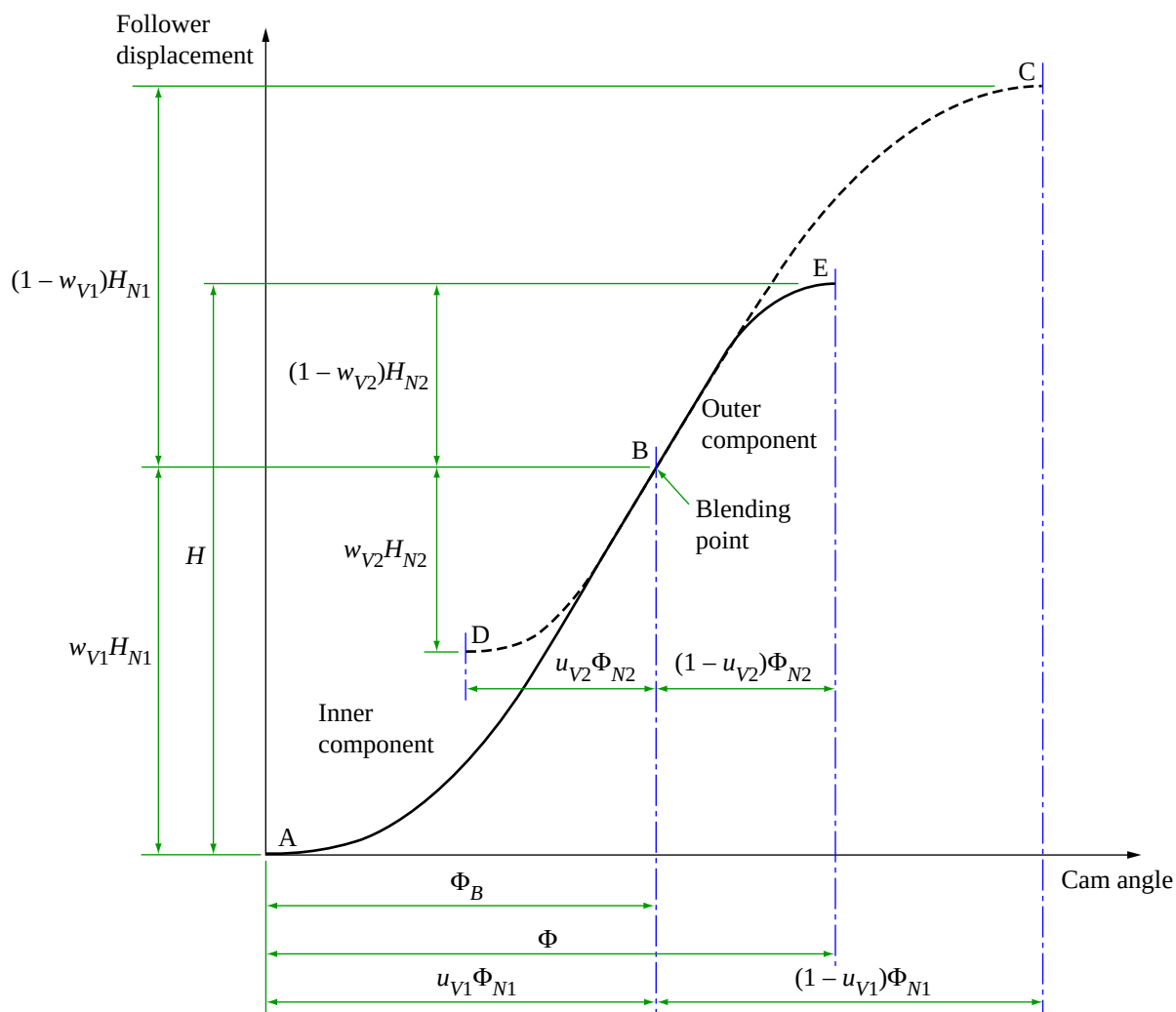
3.1.3 Blended motion and notional dimensions

This Item considers the use of motion segments formed by blending the inner component of one single-law segment[†] with the outer component of another single-law segment at the point of maximum follower velocity (see Sketch 3.2 for rise motion and Sketch 3.3 for return motion). These components are characterised by notional dimensions that are distinguished by the suffixes N1 and N2. Component AB is the inner part of a single-law motion, ABC, having a notional segment angle, Φ_{N1} and notional follower lift, H_{N1} , between the limits $0 \leq u_{N1} \leq u_{V1}$, where u_{V1} is the normalised cam displacement at the position of maximum follower velocity. Component BE is the outer part of a different single-law motion, DBE, (not necessarily the same cam law) having a notional segment angle, Φ_{N2} and notional follower lift, H_{N2} , between the limits $u_{V2} \leq u_{N2} \leq 1$, where u_{V2} is the normalised cam displacement at the position of maximum follower velocity. It follows that the notional prime circle radius corresponding to Component AB is identical to that of the actual cam but the notional prime circle radius of Component BE is given by

$$(R_a)_{N2} = (R_a)_{N1} + w_{V1}H_{N1} - w_{V2}H_{N2}. \quad (3.6)$$

Appropriate notional dimensions must be used for all calculations involving Component BE.

[†] The equations presented in this section are general in the sense that the inner and/or outer component of a blended segment can be formed using an asymmetrical cam law. However the computer program (ESDUpac A9214) caters only for segments composed from the commonly-used symmetrical cam laws in which maximum velocity occurs at mid-stroke.



Sketch 3.2 General form of non-dimensional follower motion for rise segment formed by blending two single-law motion segments

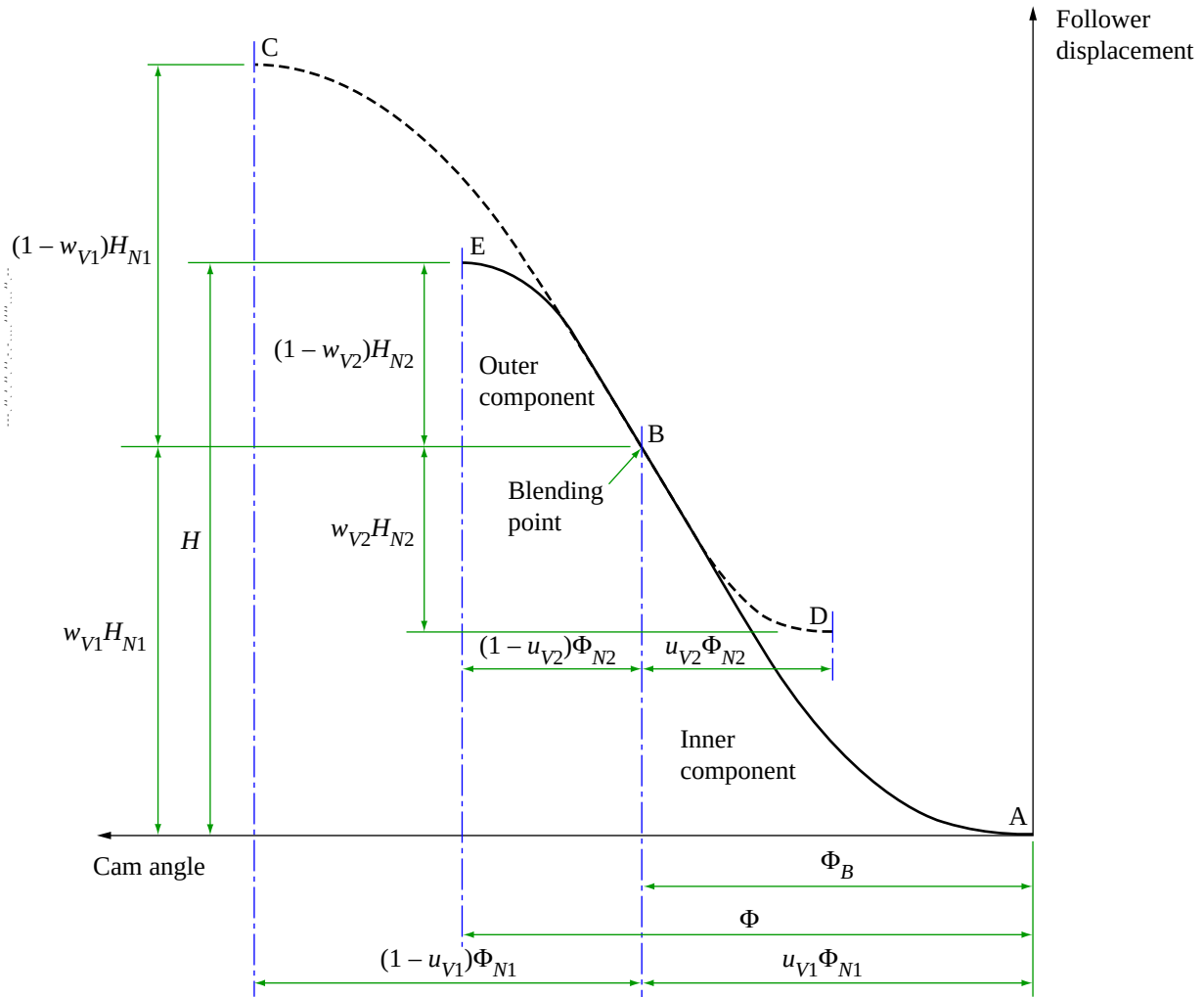
3.1.4 Proportions of blended profiles

The procedures described in this Item require that the blending point always coincides with the position of maximum follower velocity to ensure continuity of follower velocity and acceleration. The proportions of blended profiles in this Item are defined by a blending ratio given by

$$k_B = \frac{\phi_B}{\Phi}, \quad (3.7)$$

where ϕ_B is the cam angle at the blending point (measured from the beginning of a rise segment and from the end of a return segment as shown on Sketches 3.2 and 3.3).

For the purpose of blending, a return motion segment is considered to be a mirror-image of a rise segment.



Sketch 3.3 General form of non-dimensional follower motion for return segment formed by blending two single-law motion segments

Expressions for the notional dimensions of a blended motion segment, in terms of known parameters, are derived in this section. The two components of motion are blended together at the point of maximum follower velocity and so, equating the expressions (obtained by rearranging Equation (3.4)) for follower velocity at the blending point gives

$$\dot{y} = \frac{180(w'_{N1})_{max}\omega_c H_{N1}}{\pi\Phi_{N1}} = \frac{180(w'_{N2})_{max}\omega_c H_{N2}}{\pi\Phi_{N2}} \quad (3.8)$$

which leads to

$$\frac{\Phi_{N1}}{\Phi_{N2}} = \frac{(w'_{N1})_{max}H_{N1}}{(w'_{N2})_{max}H_{N2}} \quad (3.9)$$

Values of maximum non-dimensional follower velocity are given in Table 4.1 for commonly-used cam laws. By inspection of Sketch 3.2 or Sketch 3.3 it can be seen that

$$\Phi = u_{V1}\Phi_{N1} + (1 - u_{V2})\Phi_{N2} \quad (3.10)$$

and
$$H = w_{V1}H_{N1} + (1 - w_{V2})H_{N2} . \quad (3.11)$$

Note that for commonly used cam laws (*i.e.* those given in the computer program)

$$u_{V1} = u_{V2} = w_{V1} = w_{V2} = 0.5 . \quad (3.12)$$

Also, since

$$u_{V1}\Phi_{N1} = \phi_B , \quad (3.13)$$

the notational segment angle of the inner component is given, in terms of the blending ratio, by

$$\Phi_{N1} = \frac{\phi_B}{u_{V1}} = \frac{k_B\Phi}{u_{V1}} . \quad (3.14)$$

Similarly the notional segment angle of the outer component is given by

$$\Phi_{N2} = \frac{(1 - k_B)\Phi}{1 - u_{V2}} . \quad (3.15)$$

Also, by observation of Sketches 3.2 and 3.3, the notional segment angle of the outer component is given by

$$\Phi_{N2} = \frac{\Phi - u_{V1}\Phi_{N1}}{1 - u_{V2}} . \quad (3.16)$$

Equation (3.9) can be rearranged to give

$$H_{N1} = \frac{\Phi_{N1}(w'_{N2})_{max}H_{N2}}{\Phi_{N2}(w'_{N1})_{max}} = Z H_{N2} , \quad (3.17)$$

where
$$Z = \frac{\Phi_{N1}(w'_{N2})_{max}}{\Phi_{N2}(w'_{N1})_{max}} = \frac{k_B(1 - u_{V2})(w'_{N2})_{max}}{u_{V1}(1 - k_B)(w'_{N1})_{max}} . \quad (3.18)$$

Also, by observation of Sketches 3.2 and 3.3, the notional lift of the outer component is given by

$$H_{N2} = \frac{H - w_{V1}H_{N1}}{(1 - w_{V2})} . \quad (3.19)$$

Substituting Equation (3.19) into Equation (3.17) gives

$$H_{N1} = \frac{Z(H - w_{V1}H_{N1})}{(1 - w_{V2})} \quad (3.20)$$