

A COMPARISON OF TECHNIQUES FOR BALANCING PLANAR LINKAGES

1. NOTATION

Units are given in SI. However, any coherent system of units may be used

		<i>Units</i>
F_s	frame shaking force	N
$(F_s)_{rms}$	r.m.s. value of magnitude of frame shaking force	N
F_{sa}	component of frame shaking force parallel to axis of symmetry between two identical linkages	N
F_{sp}	component of frame shaking force perpendicular to axis of symmetry between two identical linkages	N
F_{sx}, F_{sy}	components of frame shaking force in x and y directions respectively	N
M_s	frame shaking moment	N m
$(M_s)_{rms}$	r.m.s. value of magnitude of frame shaking moment	N m
P_j	joint force	N
$(P_j)_{max}$	maximum magnitude of joint force during cycle	N
$(P_j)_{rms}$	r.m.s. value of magnitude of joint force	N
T_i	input torque	N m
T_{ic}	maximum peak-to-peak value of input torque during steady-state operation	N m
T_{is}	starting torque	N m
θ_2	input crank angle	degree

2. INTRODUCTION

Most planar linkages transmit a periodically-varying shaking force[†] and shaking moment[†] to the fixed frames of the machines of which they form a part. The elimination (or reduction) of this force and moment is known as balancing. This Data Item presents a basis for the comparison of the available techniques for balancing planar linkages. Firstly, the design criteria are identified and discussed (see Section 3) and, then each balancing technique is introduced and its characteristics are evaluated (see Section 4). References for further information on the component design procedures are given (see Section 5). It is wise to consider balancing at the preliminary design stage since a wide choice of possible solutions is frequently available at this point. However, this Item is also of use during detail design or development of a machine when minimisation of frame shaking force and frame shaking moment is often considered.

2.1 Definitions and Terminology

Complete definitions and explanations of the following terms with relevant examples of their use and methods for their calculation are included in References 6 and 9.

2.1.1 Frame shaking force and frame shaking moment

Forces acting at an interface between moving links and a fixed frame may be represented by a single resultant force acting at a specified point (often the input link shaft centre) and a moment about that point. The instantaneous values of this force and moment, which vary in both magnitude and direction throughout the machine cycle, are known as the frame shaking force, F_s , and the frame shaking moment, M_s . In most practical high speed machines the frame shaking force and frame shaking moment are mainly due to inertia forces associated with accelerations of moving links.

2.1.2 Joint force

The joint force, P_j , is the instantaneous force exerted by one moving link on either the fixed frame or another moving link. Joint forces vary in both magnitude and direction throughout the machine cycle.

2.1.3 Input torque

The input torque, T_i , is the instantaneous torque at the input shaft during normal operation of the linkage.

2.1.4 Planar linkage

The balancing methods presented in this Item apply strictly to planar linkages. A planar linkage is one in which the centres of mass of the moving links lie in a common plane. If more than one set of identical links is present then the global mass centres of the moving links must lie in the same plane. In practice very few linkages meet these conditions. Out-of-plane moments, which may be increased by some of the methods suggested in this Item, will be present if a linkage is not planar. Performance may be improved and analysis will be simplified if the chosen linkage is arranged, at the conceptual design stage, to resemble an ideal planar linkage. Clevis joints and dog-leg links are often used to ensure that link centres of mass lie in the same plane.

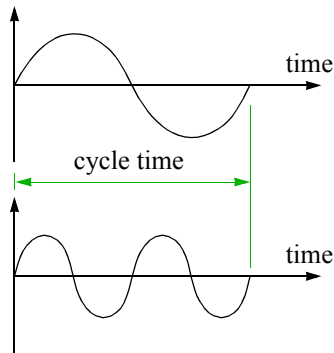
2.1.5 Rigidity of links

The balancing methods compared in this Item apply strictly to linkages with rigid moving links. The fixed frame is also assumed to be rigid. The designer should be aware that elasticity of the moving links or the fixed frame will reduce the effectiveness of all the techniques discussed in this Item.

[†] See Section 2.1.1 for definitions.

2.1.6 Frequency terminology

In order to discuss the frequency content of those parameters which change periodically it is necessary to adopt the conventions of Fourier analysis. The cycle time (C.T.) is the time taken for every moving link to complete at least one cycle during steady state operation.



first-order frequency term (fundamental)

second-order frequency term

2.2 Use of this Item

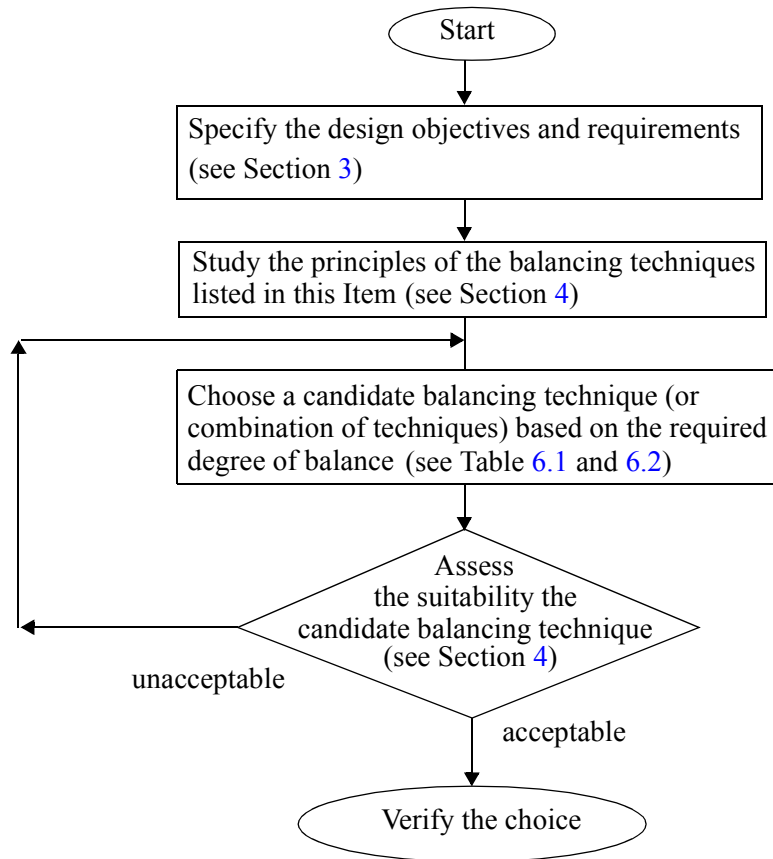
The choice of a balancing technique is an iterative process involving the consideration of many conflicting factors. The information contained in this Item may be used in a systematic way as suggested in the flowchart (see Sketch 2.1) to help the designer to select an appropriate technique. It should be noted that to verify the chosen technique it is necessary to use:

- (a) component design procedures (see References 4, 5, 7, 8, 9, 10, 11, 12 and 13) to determine the position and size of any components required to implement the balancing technique,
 - (b) force analysis calculation procedures to find the forces and torques in the balanced and unbalanced linkages (see Reference 6)
- and
- (c) machine design specifications and layout drawings to ensure that space, cost and weight restrictions are not infringed by any new components.

The verification process may highlight previously unforeseen problems. For instance:

- (i) the required components may be too large to fit in the machine,
 - (ii) bearing loads may rise unacceptably
- or
- (iii) an undesirable change in the natural frequency of certain links may occur.

In cases such as these it may be necessary to use this Item to select an alternative technique.



Sketch 2.1 Selection flowchart

3. DESIGN CRITERIA

The choice of a suitable balancing method rests on a multitude of factors, many of which are peculiar to the machine in question and to the stage in the design or development at which balancing is considered. It is always beneficial to consider the means of balancing a linkage at an early stage in its design. This section discusses the many criteria to be considered by the designer and may be used to compile a list of objectives and requirements by which the techniques may be evaluated.

3.1 The Required Degree of Balance

It is suggested in the selection flowchart (see Sketch 2.1) that a candidate balancing method may be chosen by the use of Tables 6.1 and 6.2. The designer needs to decide whether reduction or elimination of frame shaking force and/or frame shaking moment is required. Complete elimination of both of these quantities is rarely necessary and often impossible to achieve. It is generally advantageous to reduce the frame shaking force in preference to the frame shaking moment, but to determine which parameter is most likely to cause vibration and how much reduction is needed to improve performance it is useful to:

- (a) consider the relative importance of the overall machine design objectives (see Section 3.1.1),
 - (b) consider the linkage within the context of the total machine configuration (see Section 3.1.2)
- and (c) assess any existing data relating to frame shaking force and frame shaking moment (see Section 3.2).

3.1.1 Machine design objectives

A linkage will require balancing if the machine design specification contains strong requirements for:

- (a) high speed operation,
 - (b) large physical size,
 - (c) low noise,
 - (d) low vibration level,
 - (e) long component life
- or (f) positional accuracy of some machine member which is attached to the frame.

These qualities are very difficult to quantify and the adverse effects of frame shaking force and frame shaking moment can only be judged in relation to the machine configuration (see Section 3.1.2). However, in many applications one or two machine design objectives will override the others and make the need for balancing obvious. For example, high volume production machines used to form metal cans have massive links to withstand the stresses due to high internal process forces. The motions of these massive links result in a large shaking force exerted on the fixed frame leading to problems in pinning the machine to its mountings. In this application the introduction of some means of reducing the shaking force would have immediate production benefits since the machine operating speed could be increased.

3.1.2 Machine configuration

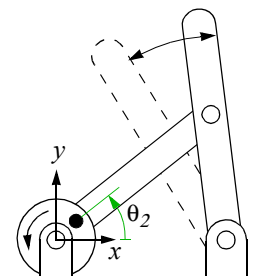
The shape and size of the frame to which the moving links are attached are usually partly determined when balancing is considered. In general, if the moving links are small and light relative to the frame, or if the

frame is extremely stiff, then balancing will be of secondary importance unless the linkage is operated at very high speed. It is important to consider the direction of the frame shaking force in relation to the configuration and stiffness of the machine frame. For example, in a domestic sewing machine the needle mechanism produces a large, variable component of force in the vertical plane. The mechanism is situated at the end of a horizontal cantilever so it is important to reduce the frame shaking force to avoid unwanted vibration in this part of the machine that may result in loss of positional accuracy between needle and shuttle.

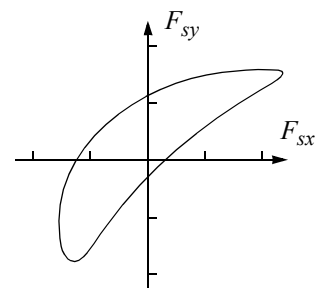
Many classes of machine stand on the floor and thus act as vertical cantilevers so it is important to reduce the frame shaking force in the horizontal plane. The natural frequency of a machine frame is generally orders-of-magnitude higher than the first-order frequency term of the frame shaking force. However, in some cases it may be necessary to remove higher order frequency terms of the shaking force that excite natural frequencies in frame components. This can be achieved by the use of a Lanchester Balancer rotating at some multiple of crank speed or, alternatively, the frame can be stiffened to increase its natural frequency. The use of anti-vibration mounts and/or vibration isolators and dampers should be considered to prevent transmission of vibration to the surroundings.

3.2 Frame Shaking Force and Frame Shaking Moment Data

The shaking force and shaking moment exerted on the machine frame by a linkage may be estimated by analysis (see References 5 and 6). The most appropriate form of presentation of the frame shaking force data, for the purpose of selecting a balancing technique, is the hodograph. This is the locus of the ends of the frame shaking force vector during the motion cycle (see Sketch 3.1). It may also be helpful to plot separately the vertical and horizontal components of frame shaking force against time (or input crank angle) as shown in Sketch 3.2. The frame shaking moment should be plotted against time (or input crank angle) for one cycle in a similar manner to the force.

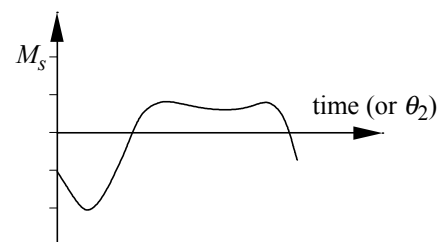
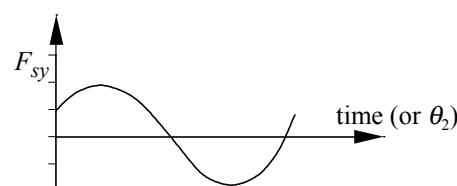
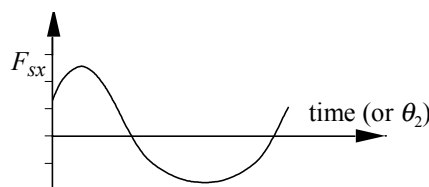


a) Four-bar crank-rocker



b) Shaking force hodograph

Sketch 3.1 Example data for four-bar crank-rocker



Sketch 3.2 Example data for four-bar crank-rocker

It is important to remember that the ideal shape of a frame shaking force hodograph is vanishingly small. This condition can be attained theoretically in many linkages by the use of methods in Tables 6.1 and 6.2. However for practical reasons, outlined in Section 4, these methods are often infeasible. The methods which reduce the frame shaking force by exerting an opposing force on the machine frame may be very effective if the hodograph of the original linkage approximates to certain shapes. It may be possible to choose a candidate balancing method directly by inspection of the hodograph in these cases.

(a) Circular hodograph

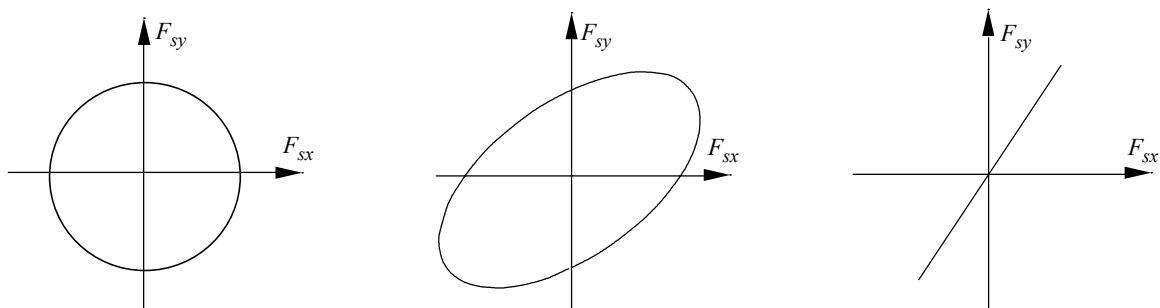
If the linkage hodograph is approximately circular, as shown in Sketch 3.3(a), and the frame shaking force vector rotates once during one cycle sweeping through equal angles in equal times a single counterweight (see Section 4.2) attached to the input link will result in a large reduction in this force.

(b) Elliptical hodograph

Since the Generalised Lanchester Balancer (see Section 4.9) may be designed to produce an elliptical frame shaking force hodograph having any axis ratio it can be used effectively to balance a linkage which displays a hodograph of approximately this shape. Note that the frame shaking force vector of a Generalised Lanchester Balancer as shown in Sketch 3.3(b) sweeps equal areas in equal times.

(c) Straight line hodograph

A linkage demonstrating a hodograph which is approximately a straight line as shown in Sketch 3.3(c) may have its frame shaking force reduced effectively if a Lanchester Balancer (see Section 4.8) is incorporated in the machine.



Sketch 3.3 Regular hodographs

The three regular hodographs ((a), (b) and (c)) are special cases of curves known as Lissajous Figures. These are the patterns traced out when two sinusoidally varying quantities are superimposed at right angles to each other. More complicated patterns than those shown in Sketch 3.3 result when the ratio of frequencies of the component sine waves is not an integer. If a hodograph is recognised as being a Lissajous Figure the frame shaking force may be effectively reduced by two masses rotating at certain angular velocities with a particular phase relationship. If the hodograph displays irregular loops, cusps or abrupt changes of curvature then the methods of decreasing the shaking force using rotating masses may not result in worthwhile reductions.

Ideally the frame shaking moment should be zero throughout the cycle. This condition can be attained theoretically, in many linkages, by the use of certain methods (see Tables 6.1 and 6.2). These methods may be inadvisable for practical reasons outlined in Section 4. If the frame shaking moment graph is dominated by a single frequency term (*i.e.* approximates to a sine wave) then this moment may be reduced effectively by the use of rotating or oscillating masses.

3.3 The Effect of Balancing on Joint Forces

The force transmitted at a joint between two links is a function of inertia forces, drive and process forces and torques (both internal and external) and forces due to friction, windage and static weight of the moving links. Balancing methods may affect the components of joint forces due to inertia and weight of the moving links.

If, due to the implementation of a balancing technique, the mass, position of centre of mass or moment of inertia of any link is altered, then the magnitude and direction of the force at the joints connecting that link to other links will also change. In general an increase in link mass, due to the addition of counterweights to moving links, causes an increase in both the r.m.s. and peak values of joint force at each joint. This increase can be minimised by the careful choice of counterweight shape (see Reference 7). Balancing methods in which existing links are not altered will not affect the forces at the joints of the linkage.

It may be useful to compare hodographs of joint forces for balanced and unbalanced linkages in order to assess the effect of balancing upon both r.m.s. and peak values of the force. However, it may be more important to consider the shape of the hodograph. A roughly circular or elliptical pin joint hodograph is often acceptable since this demonstrates that the pin joint force does not change its magnitude or direction rapidly and contact in the bearing is likely to be maintained. An irregular hodograph with cusps, loops and rapid changes in the magnitude of the force vector is undesirable and so is a hodograph in which the joint force vector passes near to the origin because this shows that loss of contact and therefore high impact force is likely in the bearing. By placing springs between two moving links (or between a moving link and the frame) individual pin joint force hodographs may be modified so that they become more regular in shape thus improving bearing loads. It should be noted that while springs cannot be used to alter the theoretical frame shaking force hodograph (obtained by ignoring impact forces in the bearings) they may, in practice, reduce the component of frame shaking force due to impacts.

3.4 The Effect of Balancing on the Input Torque

The input torque comprises:

- (a) the inertia torque during acceleration to steady-state operating speed,
 - (b) the variable torque due to the change in inertia forces during steady-state operation
- and
- (c) the torque due to any external or internal process forces and/or moments applied to the linkage during the working cycle (including friction and windage).

For a general linkage these effects are illustrated in Sketch 3.4 where the torque is assumed to be positive when energy is supplied to the linkage and negative when the linkage feeds energy back to the prime mover.

If, as a part of the balancing procedure, mass is added to links or shafts which rotate with nominally constant angular velocity during steady-state operation (*i.e.* crankshaft counterweights or Lanchester Balancers) then the required starting torque is increased. The machine may require a larger prime mover and a larger brake to maintain the same acceleration and retardation times. Mass added to parts which move with variable angular velocity during steady-state operation (*i.e.* counterweights added to rockers and couplers or duplicate linkages) increases the peaks of the torque oscillations as well as increasing the starting torque. Such linkages may require larger flywheels and possibly larger prime movers to ensure that the variations in speed are acceptable. The fluctuations in input torque may be reduced by the use of springs placed between two moving links or between a moving link and the frame.