

REDUCING TORQUE FLUCTUATION IN LINKAGE DRIVE SHAFTS

1. NOTATION AND UNITS

The units used in this Item are SI but any coherent system of units may be used.

		Units
F_s	frame shaking force	N
M_s	frame shaking moment	N m
P_{ij}	force exerted by link i on link j	N
P_{xij}, P_{yij}	components of joint force P_{ij} in x - and y -directions, respectively	N
T_i	magnitude of shaft torque	N m
T_{ic}	maximum peak-to-peak value of shaft torque during steady-state operation	N m
T_{is}	starting torque	N m
θ_2	input crank angle	degree

2. INTRODUCTION

Linkages are used in many machines to transmit motion and power. There is often a requirement for the linkage to drive, or be driven by, a shaft rotating continuously with nominally constant angular velocity. The torque experienced by such shafts varies due to the inertial and gravitational effects of the moving links together with the influence of any variable external forces or torques acting on those links. During steady-state operation of the machine the shaft torque and shaft angular velocity vary cyclically with a period equal to the time taken for every moving link to complete at least one cycle. This fluctuation can cause problems in applications that require a linkage to operate at high speed.

This Data Item presents and compares a number of techniques used to reduce the shaft torque fluctuation. The design criteria are identified and discussed in Section 3. The principle of each technique is explained and its characteristics are evaluated in Section 4 while Section 5 contains references for further information on the design of individual components.

Use of this Item will lead to an informed choice of technique for reducing torque fluctuation. Subsequent implementation of the chosen technique could lead to increased machine component life, increased allowable operating speed, use of a less expensive prime mover and reduced machine noise.

It is advantageous to recognise the need to control torque fluctuation during preliminary design because a wide range of potential solutions is frequently available at this stage. However, this Item is also of use during detail design or development of a machine when the problem is more often confronted.

2.1 Definitions and Terminology

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. 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_{ij} , is the 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 (see Sketch 3.2).

2.1.3 Shaft torque

The torque, T_p , is the value of torque at the shaft connected to the linkage. This torque fluctuates and the difference between the extreme values during steady-state operation is referred to as the peak-to-peak torque, T_{ic} (see Sketch 3.1). The starting torque, T_{is} , is the torque required to move the linkage from rest. This value may vary depending on the initial position of the linkage.

2.1.4 Stiffness of links

The methods compared in this Item apply strictly to linkages with "rigid" moving links. The fixed frame is also assumed to be rigid. Significant deflection of the moving links or the fixed frame may reduce the effectiveness of some techniques.

2.1.5 Hodographs

Joint forces and shaking force are conventionally illustrated using hodographs. A hodograph is the locus of the ends of a series of force vectors calculated at intervals during one complete cycle (see Sketch 3.2 and Section 3.2).

2.2 Reasons for Reducing Torque Fluctuation

It may be desirable to reduce the fluctuation of shaft torque for one or more of the following reasons.

- (a) Torque fluctuation is accompanied by a corresponding variation in shaft angular velocity. If the shaft in question drives a linkage the variation may adversely affect the motion-time response of the output link and so lead to machine timing problems. For example, a variation in the angular velocity of the drive shaft of a high-speed press, based on a slider-crank mechanism, could result in scrap production if the tool does not contact the workpiece when expected. This problem is particularly acute because the angular velocity of the input shaft is often assumed to be constant during kinematic design of linkages.
- (b) Fluctuation of shaft torque may degrade the performance of a prime mover used to drive a linkage. In extreme cases the peak value of shaft torque could be high enough to stall the prime mover. Conversely, it may be possible to specify a less powerful and less expensive prime mover if torque fluctuation is minimised.

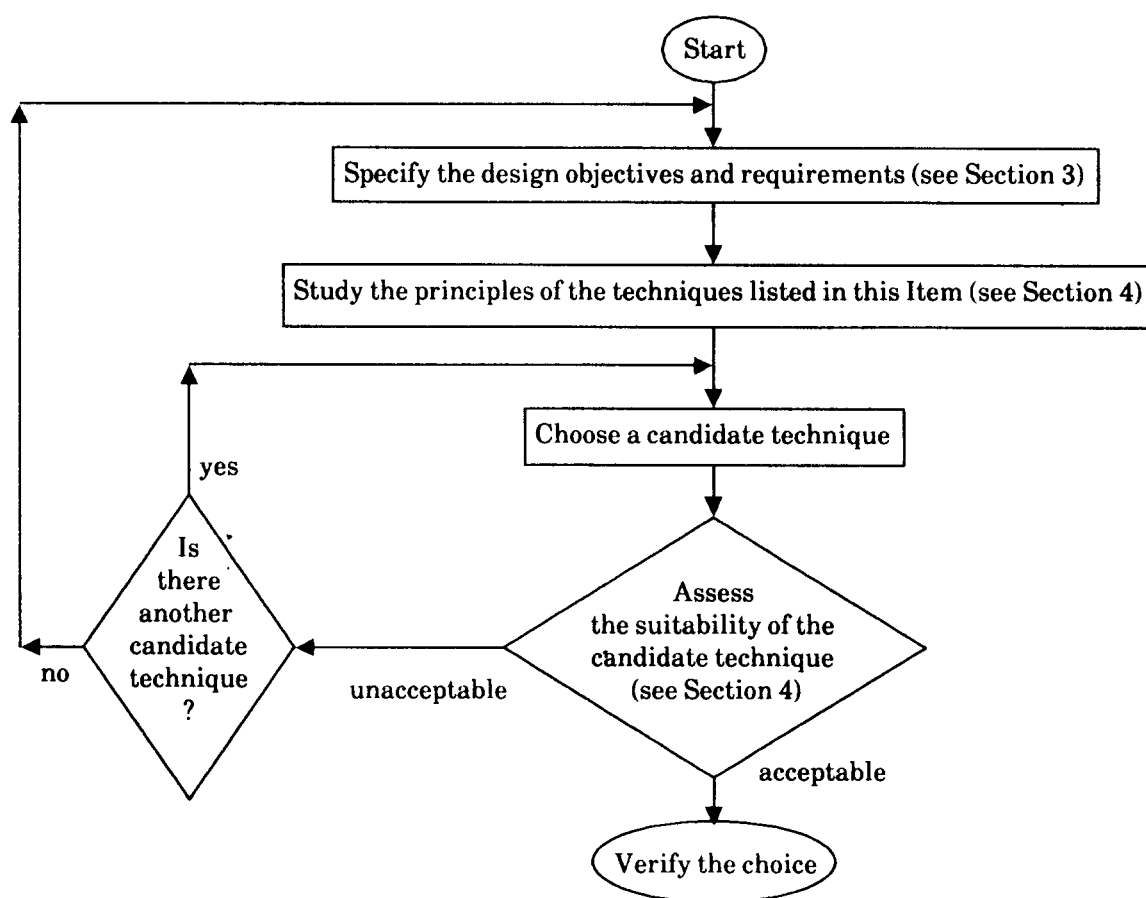
- (c) Fluctuating torque may be responsible for the premature failure of drive shafts, gearing, transmissions or other machine components by fatigue or wear. Therefore reduction of the peak-to-peak torque may result in increased machine life and reduced noise levels.

In practice some torque fluctuation is always present. The aim is to match, as closely as possible, the characteristics of the prime mover, transmission system and linkage (see Reference 21).

2.3 Use of this Item

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

- (a) component design procedures to determine the position and size of the necessary components (see Section 3.7),
 - (b) calculation procedures to estimate the torque in the shaft and, possibly, the forces at the bearings, both before and after implementation of any technique (see Derivation 1 and References 11 and 18)
- and
- (c) machine design specifications and layout drawings to ensure that space, cost and weight restrictions are not infringed by any additional components.



Sketch 2.1 Selection flowchart

2.4 Design Guidance

The verification process may highlight previously unforeseen problems and the following points may help to identify and solve those problems.

- (1) Always consider the kinematic design of the linkage from the point of view of dynamic performance. Ensure that transmission angles do not deviate greatly from 90° during the motion cycle (see Reference 9). It is also advisable to minimise the clearance at joints and to ensure that contact at each joint is maintained so that torque fluctuation due to backlash is avoided.
- (2) Determine the major cause of harmful torque fluctuation. Inertial effects, gravitational effects and external forces acting on the linkage during the operating cycle should be considered. The dominant factor in a particular application may be known by experience or intuition but it may be necessary to estimate the shaft torque due to each effect separately. If external forces or torques make a significant contribution to the peak-to-peak variation in shaft torque, consider the operation of the machine with a view to reducing their magnitude. If inertial or gravitational effects are dominant choose a technique that reduces selectively their influence on the shaft torque.
- (3) Fluctuation of shaft torque may lead to torsional vibration of the drive shaft. The magnitude of this vibration may become excessive if resonance occurs. Therefore it is advisable to estimate the low-order frequency terms (harmonics) of the torque and ensure none approximates closely to any natural frequency of the shaft (see Reference 5).
- (4) For those solutions that affect values of joint forces check that magnitudes do not exceed maximum allowable bearing loads and check that the likelihood of contact loss is not increased (see Section 3.2).
- (5) For those solutions that affect adversely the balance of the linkage check that increases in frame shaking force and frame shaking moment do not result in unacceptable vibration of the machine frame. Consider a combination of techniques to reduce torque fluctuation and balance the linkage (see Reference 8).
- (6) For those techniques that result in increased starting and braking torque check that the modified values do not exceed design requirements.
- (7) If it is discovered during verification that there is not enough room for the components required to implement the chosen technique, consider a partial solution using components designed to fit into the available space.

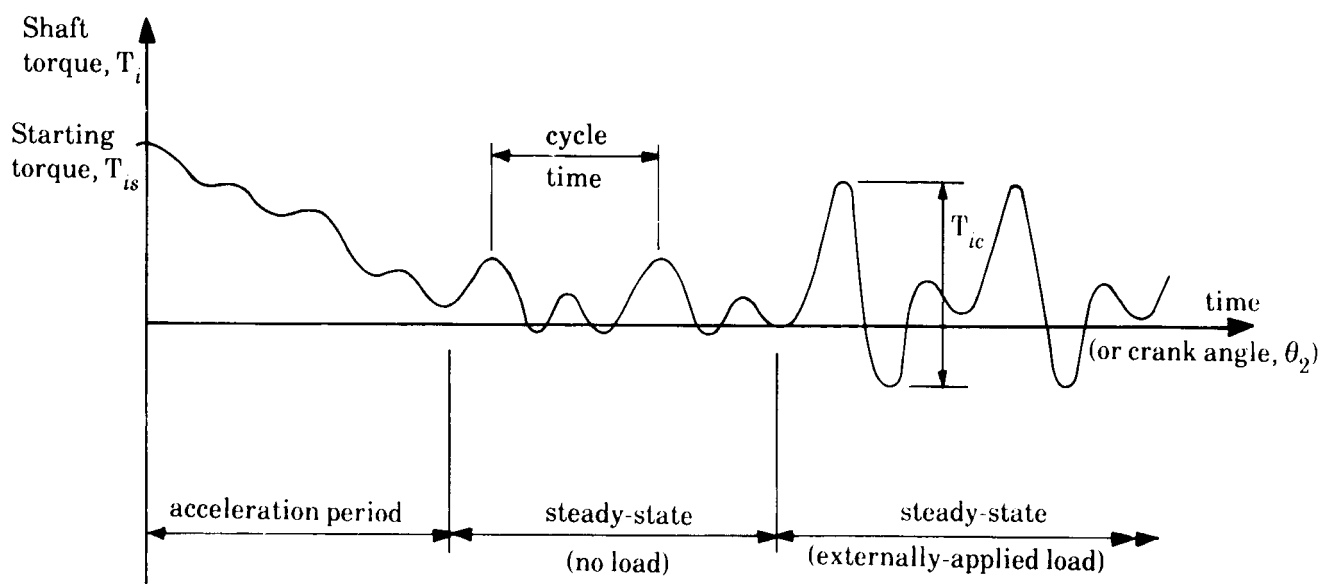
3. DESIGN CRITERIA

The choice of a suitable technique 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 torque fluctuation is considered. It is always beneficial to consider the problem of reducing torque fluctuation at an early stage in the linkage design. The relevant criteria by which to judge potential solutions are discussed in this section. These may be used to compile a list of objectives and requirements for the design.

3.1 Effect on Shaft Torque

A typical graph of drive shaft torque against time is shown in Sketch 3.1. 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. The torque at start-up is high and decreases as the linkage approaches steady-state operation. Fluctuation due to inertial and gravitational forces is shown during off-load operation. The additional fluctuation due to variable external load is shown during normal (on-load) operation.



Sketch 3.1 Drive shaft torque against time

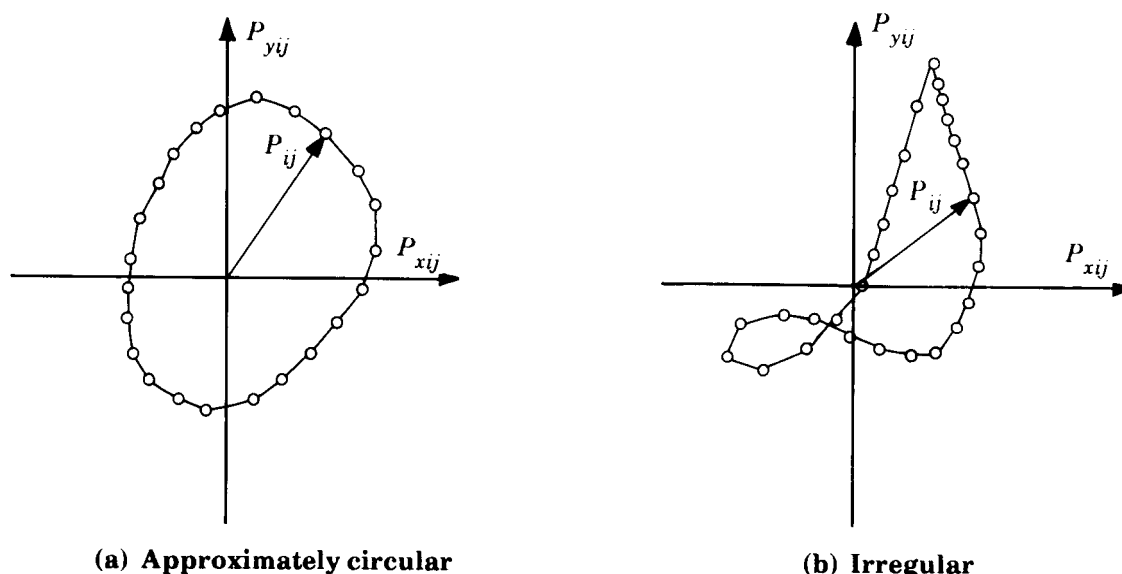
Accurate values of shaft torque for high-speed linkages are difficult to obtain by calculation. Kinetostatic force analysis (for planar linkages see Reference 11) can be used to give the torque required to maintain the assumed motion (usually constant angular velocity) of the input shaft. Torque values obtained by kinetostatic analysis are very useful for comparing the relative effects of the different techniques recommended in Section 4 but they should not be regarded as absolute values. To obtain a more accurate estimate of the shaft torque a dynamical model of the system, possibly including the characteristics of the prime mover, is necessary (see References 11 and 25). Alternatively, shaft torque may be measured directly or indirectly (by measurement of shaft strain) in an existing machine.

Each technique suggested in Section 4, except the flywheel, can be used to reduce the peak-to-peak variation in shaft torque during steady-state operation but some methods affect other aspects of the torque. For instance, the starting torque may be increased and the amplitudes of certain frequency terms may be altered. It is not possible to recommend a generally acceptable peak-to-peak magnitude of input torque fluctuation. A satisfactory level is attained if the chosen prime mover can drive the linkage such that the motion-time response of the output link is within its specified performance envelope and the integrity of the shaft is maintained for a satisfactory lifetime.

If the design is at an early stage it is advisable to minimise torque fluctuation before choosing a prime mover. If the design is at an advanced stage and the prime mover has been chosen, and possibly installed, the target level of fluctuation may be specified exactly.

3.2 Effect on Joint Forces

Some techniques affect values of joint force and, if this is the case, those values should be recalculated to ensure that allowable bearing loads are not exceeded. It may also be useful to compare hodographs (see Sketch 3.2) of joint forces before and after the implementation of a particular technique.



Sketch 3.2 Joint force hodographs

A roughly circular or elliptical pin joint hodograph is often acceptable since this demonstrates that the force does not change its magnitude or direction rapidly and so 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 (see Reference 6). 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. This technique may also reduce the torque fluctuation (see Method 5 in Section 4.5).

3.3 Effect on Linkage Balance (Shaking Force and Shaking Moment)

Some torque reduction techniques alter the balance of the linkage. It may be possible to reduce the shaking force and/or the shaking moment as well as the peak-to-peak torque but this is not usually the case. It is wise to consider balancing the linkage at the same time as reducing torque fluctuation. Data Item 89043 (Reference 10) contains a comparison of methods for balancing planar linkages.

3.4 Cost Considerations

It is important to consider the cost of reducing torque fluctuation relative to the overall cost of the machine. In some applications minimising the fluctuation may be vital in order to fulfil the design specification in spite of additional cost. When shaft vibration limits the speed of a production machine the cost of reducing the torque fluctuation should be compared with the benefits of increased production that could result from raising the operating speed. The relative importance of design costs will be diminished if large numbers of a particular linkage are to be manufactured. Use of methods that involve extra components, such as springs, may include hidden costs associated with decreased reliability. It is essential to consider the overall cost, that is, the cost of manufacture, design, installation, maintenance and replacement.

It is not possible to rank the methods presented in this Item in terms of cost without considering circumstances affecting the particular application or the resources available to the design team. The statements in Section 4 attempt to identify the costly aspects of each method but even these may be misleading. For instance, the costs involved in designing an extra dyad (Method 4) will be high if each trial