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# *Technical Note*

## The 1-4-1 system of jack movements for the flexible liners of supersonic wind tunnels

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## 1. INTRODUCTION

A method of improving the flow angle and Mach number distribution of a flexible-plate supersonic wind tunnel by small movements of the top and bottom liners has been known for a number of years[1]. Once the influence on the flow, at a given Mach number, of small displacements of jacks supporting the liners are known, jack movements can be used to reduce non-uniformities in the working section flow. Such a procedure is being studied for adjusting the flow in the 8 ft × 8 ft Supersonic Wind Tunnel at RAE Bedford. However, one of the main difficulties encountered has been that of accurately determining the influence of each jack. The extended rippling in the plate which results from a displacement of a single jack generates a Mach number disturbance which is difficult to trace. This is particularly true at lower Mach numbers (i.e. near $M = 1{\cdot}4$) where the reflection of the disturbance from the opposite wall is observed to combine with the 'tail' of the direct effect, thereby causing interference effects in the data. Even with a 9-tube pitot rake spanning the tunnel it is difficult to ascertain which part of the disturbance is coming from the top of the tunnel and which part from the bottom. Ways have therefore been considered of moving the plate in the region of a particular jack in such a manner that the resulting waveform is shorter and more readily traced. A simple but effective system of jack movement has been derived and is described here as the 1–4–1 system.

Section 2 is a discussion of the effect of a single jack movement. Section 3 describes the smoother 1–4–1 system of jack movement, and experimental data verifying the theory is discussed in section 4.

## 2. SINGLE-JACK MOVEMENT

In this section, the simplified problem of the small deflection of a flat plate is considered. The results give an indication of the size and extent of rippling in the plate when a single jack is moved.

The derivation of the ripple heights follows the method given by Thompson[3] with the following assumptions:

(*i*) the plate thickness does vary along its length;
(*ii*) the plate is supported at regular intervals along its length;
(*iii*) the only forces acting on the plate are the jack loads at the support points and an external couple at each end.

Assuming beam theory[2] represents adequately the normal deflections along the plate, the deflected shape between adjacent jacking stations will be cubic in form. The overall curvature can therefore be represented by a series of cubic splines with the continuity of the deflection and its first and second derivatives at each jack position determining the shape the plate will take.

For movement of a single jack, there are ripples in the plate on either side of the jack which is moved (*see* Fig. 1). Referring again to Fig. 1, the deflected shape is a series of $N$ cubics; the general equation of the $r^{\text{th}}$ cubic can be expressed as:

$$y_r = a_r X_r^3 + b_r X_r^2 + c_r X_r + d_r$$

where $y_r$ is the displacement for $(r-1)\,l \leqslant x \leqslant rl$,

$$X_r = x - (r-1)\,l \quad (l = \text{spacing of the jacks})$$

and $y_r$ and $x$ are measured normal and along the plate respectively.

The following end conditions are assumed:

(*i*) At position O, the height of the plate is $y_O$ and the gradient is zero.
(*ii*) At position N, the deflection of the plate and the second derivative of the deflection are both zero (known as a 'natural spline' condition).

At all other jack positions, continuity of deflection and its first and second derivatives determine the constants $a_r$, $b_r$, $c_r$ and $d_r$.

Denoting the maximum height of the ripple on the $r^{\text{th}}$ curve as $y_r\star$, the values of $y_r\star$ for the first five successive ripples away from the main jack movement $y_O$, are found to be as follows:

$$\frac{y_2\star}{y_O} = -0{\cdot}137$$

$$\frac{y_3\star}{y_O} = 0{\cdot}036$$

$$\frac{y_4\star}{y_O} = -0{\cdot}010$$

$$\frac{y_5\star}{y_O} = 0{\cdot}003$$

$$\frac{y_6\star}{y_O} = -0{\cdot}001$$

and so on.

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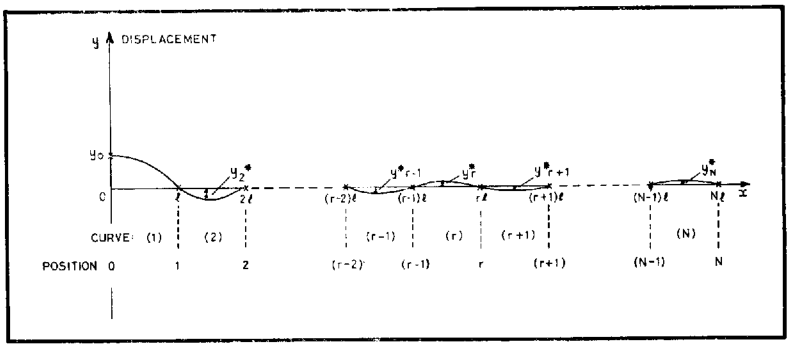


*Figure 1.* Bending of flexible plate subjected to single jack movement.

Thus for movement of a single jack, the secondary ripple is approximately 14% of the jack movement, and the ripples damp down to 1% of the jack movement between the third and fourth jacks away from the displaced jack (Fig. 2). For a jack movement near the end of the plate the approximation is less accurate but the rippling is still expected to be severe.

### 3. The 1–4–1 SYSTEM

In order to eliminate the rippling in the plate described in the previous section, a system of jack movements is required such that at the second jack position to either side of the jack primarily being moved, the associated deflection of the plate is zero and has zero first and second derivatives. The variation in slope is assumed small so that the displacement of three typical adjacent jacks can be considered to be parallel.

In Fig. 3 position 3 corresponds to the jack primarily being moved and positions 2 and 4 to the jacks on either side. The following conditions define the deflected shape:

(*i*) Continuity of deflection and its first and second derivatives along the plate.

(*ii*) At positions 1 and 5 the values of the displacement and its first and second derivatives remain unaffected by the jack displacement imposed at position 3.

If the movement of the jacks at positions 2, 3 and 4 is $y_{s1}$, $y_t$ and $y_{s2}$ respectively then both $y_{s1}$ and $y_{s2}$ can be found in terms of $y_t$.

On the same basis as was used in section 2, using the above conditions, the following result is obtained:

$$y_{s1}=y_{s2}=\tfrac{1}{4}y_t.$$

Thus, whatever the initial (small) deflection of the plate, an additional deflection which incurs no rippling can be obtained by moving the jacks on either side through a quarter of the movement of the jack primarily being displaced. In particular, for a flat portion of the plate, the 1–4–1 system brings the plate to a point of zero gradient beyond two jacks away from the central position (Fig. 4). Figure 2 and Fig. 4 show the resulting waveform from a single jack movement and a 1–4–1 jack movement, respectively.

### 4. EXPERIMENTAL TEST DATA

The beneficial effects of using the 1–4–1 system can be illustrated using data obtained from a 9-tube pitot rake in the RAE 8 ft × 8 ft wind tunnel. The plots shown in Figs. 5 to 9 for the tunnel centreline and for the liners denote Mach number increments $\Delta M$ derived from the change in pitot readings caused by the jack movement indicated in the particular figure[4].

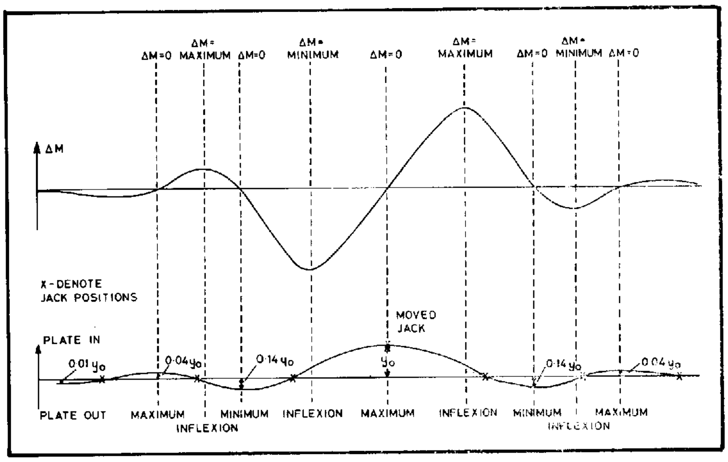


*Figure 2.* Approximate curve formed by flexible plate due to single jack movement, with resulting Mach number disturbance.

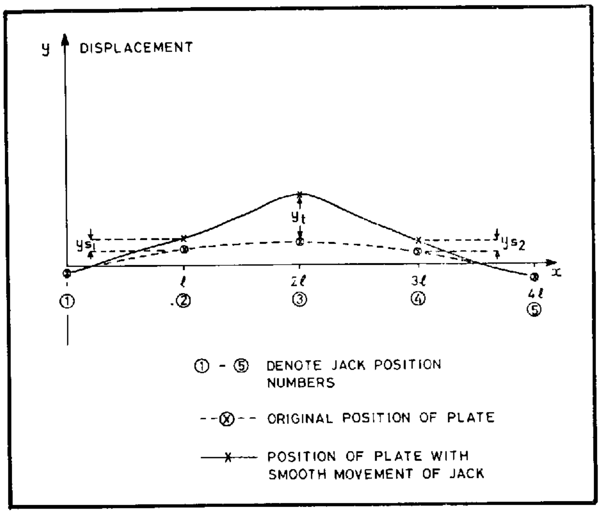


*Figure 3.* Smooth system of jack movement.

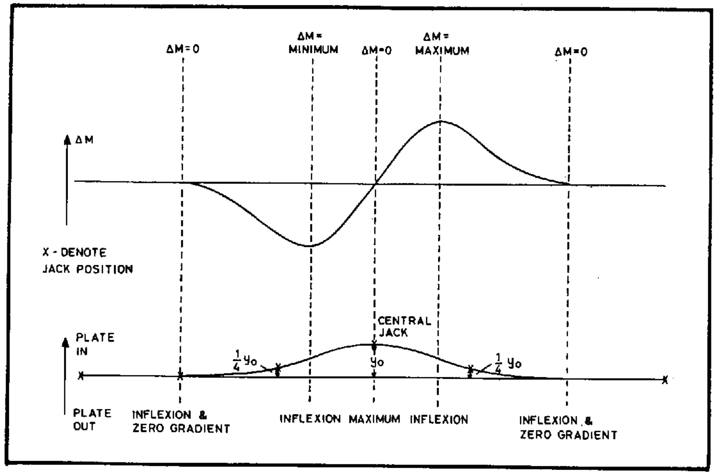


*Figure 4.* Curve formed by flexible plate with 1–4–1 deviation, with resulting Mach number disturbance.

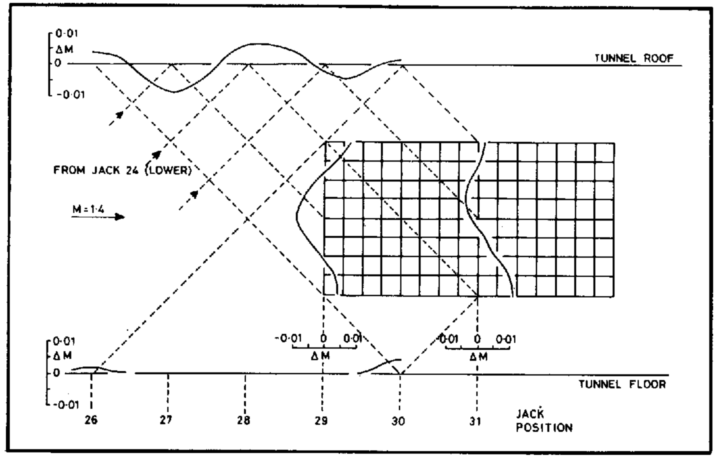


*Figure 5.* Effect in $\Delta M$ of total single movement of 0·1524 cm (0·060 in) of jack 24 (lower) at two pitot rake positions at $M$=1·4. Interference due to length of wave is demonstrated. (RAE Bedford 8 ft × 8 ft wind tunnel.)

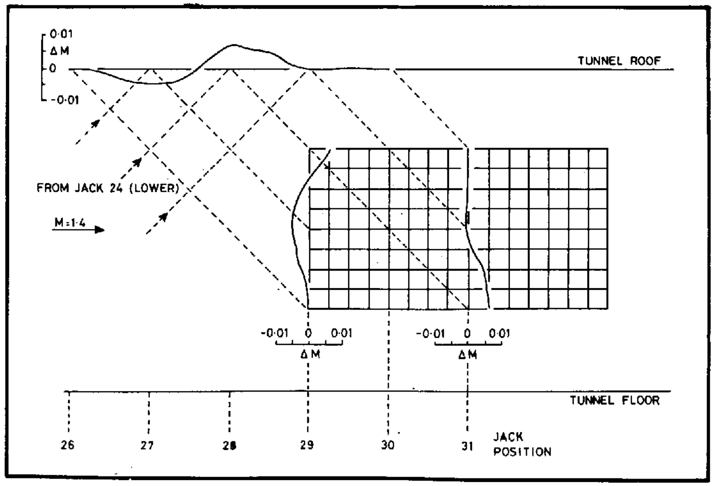


*Figure 6.* Effect in $\Delta M$ of 1–4–1 system centred on jack 24 (lower) at two pitot rake positions at $M$=1·4. Central jack moved a total of 0·1524 cm (0·060 in). (RAE Bedford 8 ft × 8 ft wind tunnel.)

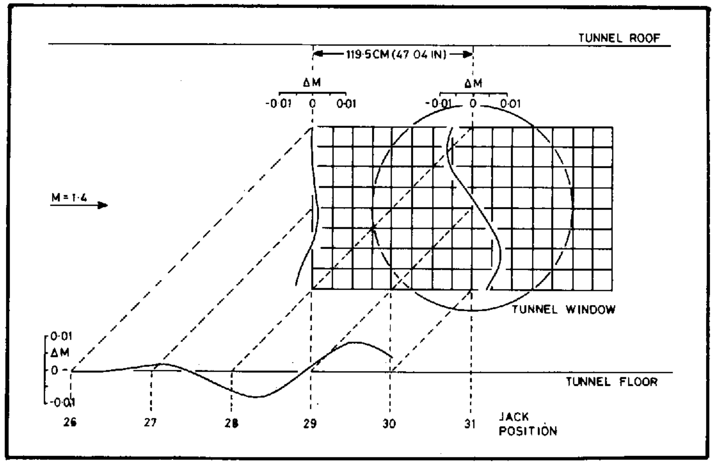


*Figure 7.* Effect in $\Delta M$ of total single movement of 0·1524 cm (0·060 in) of jack 29 (lower) at two pitot rake positions at $M$=1·4. (RAE Bedford 8 ft × 8 ft wind tunnel.)

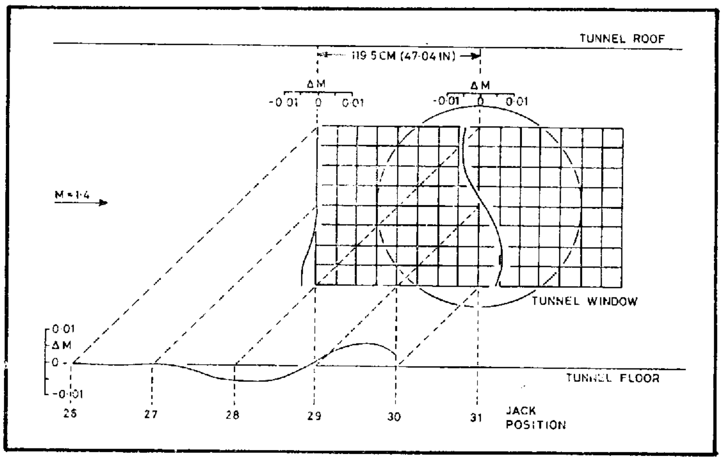


*Figure 8.* Effect in $\Delta M$ of 1–4–1 system centred on jack 29 (lower) at two pitot rake positions at $M=1\cdot4$. Central jack moved a total of 0·1524 cm (0·060 in). (RAE Bedford 8 ft × 8 ft wind tunnel.)

Figure 5 demonstrates the interference encountered when one jack only is moved, at $M = 1{\cdot}4$. When the 1–4–1 system is used, centered on the same jack (24 lower), the disturbance wave is shortened (see for example, the plot of $\Delta M$ for the tunnel roof in Figs. 5 and 6) and is therefore more easily traced from the two rake positions shown. Jacks nearer the working section have only direct effects on the working-section flow, as shown for the displacement of jack 29 lower in Figs. 7 and 8. However, it can be seen that the 1–4–1 system in Fig. 8 causes a simpler disturbance than that obtained for the single jack movement shown in Fig. 7.

At higher Mach numbers the greater slope of the Mach lines reduces any likelihood of interference causing difficulty in the tracing of a $\Delta M$ disturbance emanating from a particular jack. Nevertheless, when correcting the flow at any Mach number using plate displacements, it is desirable to restrict the region of flow disturbance resulting from a particular jack by localising the plate movement using the 1–4–1 system. Figure 9 shows the shortening and smoothing effect of the 1–4–1 system on the $\Delta M$ disturbance, when applied to a lower surface jack (27 lower) at $M = 2{\cdot}2$.

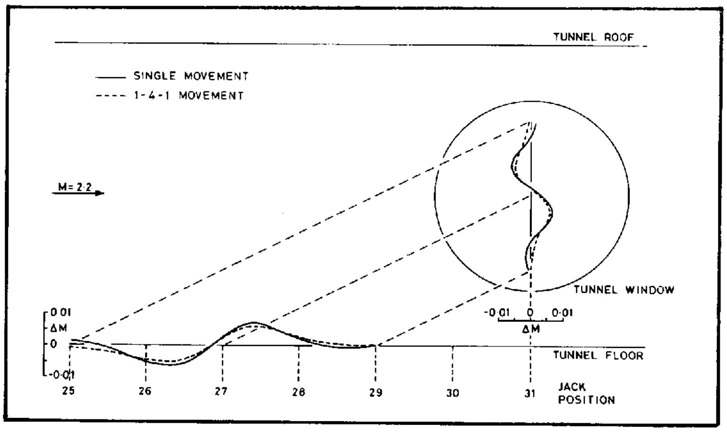


*Figure 9.* Comparison of single and 1–4–1 movement centred on jack 27 (lower) at $M=2\cdot2$. In both cases, central jack moved a total of 0·1524 cm (0·060 in). (RAE Bedford 8 ft × 8 ft wind tunnel.)

## 5. CONCLUSIONS

A new method has been proposed for finding the effects in supersonic flow of small movements of the plates of a flexible-liner wind tunnel. Previous methods involve moving a support jack on its own and have caused rippling in the plate, leading to a lengthy Mach number disturbance which is difficult to trace at low supersonic Mach numbers. Using beam theory, a system (known as the 1–4–1 system) has been derived which involves the movement of three adjacent jacks through displacements in the ratio 1 : 4 : 1. Such a system localises the rippling of the plate, and tests have clearly indicated both the shortening and smoothing effect that the system has on the resulting $\Delta M$ disturbance.

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