The Aerodynamics of Javelin Flight-A Re-Evaluation

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INTRODUCTION

Although the throwing events were a feature of the ancient Olympics, there is no indication that Aristotle or any of his colleagues conducted systematic evaluations of the javelin's fligh characteristics. It is only in the second half of the 20th century that wind tunnel tests have been carried out to determine the aerodynamic forces acting on the javelin (Ganslen, 1960; Terauds, 1972; Best and Bartlett, 1987b, c). These wind tunnel tests seek to simulate the flight of the javelin, however those reported to date have been conducted on non-spinning javelins with the relative velocity vector in the vertical plane containing the longitudinal axis of the javelin. Furthermore the javelin in the wind tunnel does not vibrate in a way comparable with that often experienced at release. Thus in at least three important respects, these wind tunnel tests fail to replicate completely the field conditions. No quantitative evaluation of these effects has been found in the literature.

The release of the javelin determines its subsequent flight and important parameters are: — release speed (vo), release angle (ao), release angle of attack (bo), release attitude angle (co), release height (zo), front foot to foul line distance (do) (figure 1), and the angular velocity components about the longitudinal axis of the javelin (spin, so), about a perpendicular horizontal axis (pitch rate, wo) and about a third axis which is mutually perpendicular to the other two (yaw rate, yo).

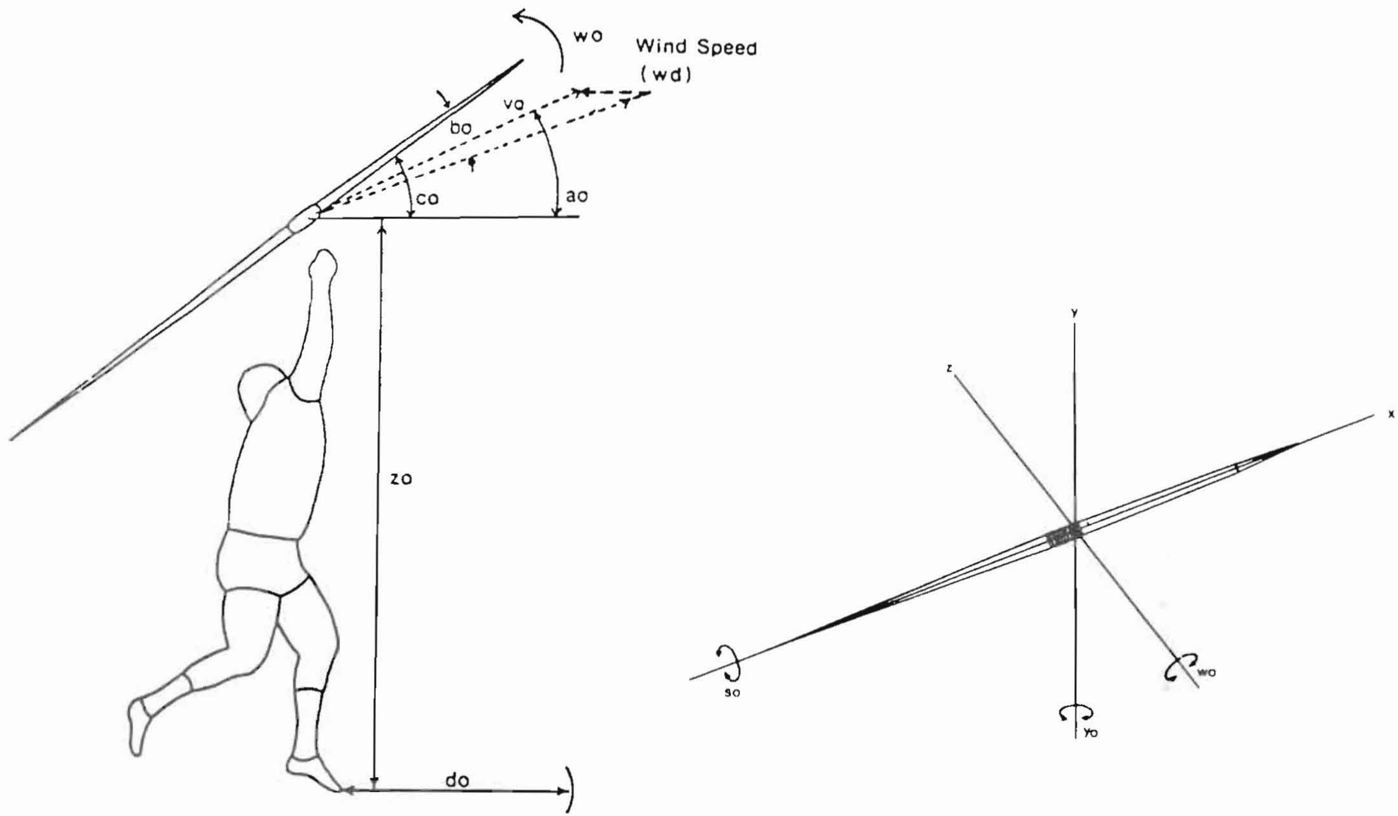

Fig. 1

Other important factors are the flutter of the javelin at release, environmental conditions, especially wind velocity and air density, and the physical characteristics of the javelin, e.g. mass, principal moments of inertia, planform area and shape. All of these affect the distance that the javelin is thrown and relate to the aerodynamic forces and moments acting on it during flight.

The aerodynamics of javelin flight now requires re-evaluation, following the International Amateur Athletics Federation rule change implemented on April 1st 1986. This involved revisions of the javelin design specifications for the men's event. The major changes are a shift of the centre of mass 4 cm towards the tip and an increase in the minimum allowable diameter of the tail section. These revisions were implemented despite the protests of javelin throwers, coaches and manufacturers, in an attempt to reduce the distance thrown, to increase the likelihood of the javelin sticking into the ground and to overcome its pitching and yawing instability, thus minimising the danger to other athletes and officials. These intended changes certainly occur as instanced by a range reduction of 12 to 13%, reported by Terauds (1985), whilst Watman (1986) found fall-offs of between 1.52 and 14.34 metres (mean 7 m) for the World's top twenty male throwers using the new rules javelins.

AERODYNAMIC FORCES

The javelin is an aerodynamic body of high fineness ratio (Ganslen, 1960) and a full understanding of the aerodynamics of such an implement (e.g. McCormick, 1979) is imperative in order to be able to optimise release parameters and hence throwing performance. In this paper, the usual procedure is adopted of assuming that the aerodynamic pressure distributions around the javelin can be considered equipollent to a single aerodynamic force intersecting the longitudinal axis of the implement at the centre of pressure (CP). The flight of the javelin then depends on the direction and magnitude of the aerodynamic force vector and the position of the centre of pressure relative to the centre of mass of the javelin, these variables being functions of the javelin's speed and angle of attack and, hence, of time.

The force system just described can be replaced by that shown in figure 2, in which the aerodynamic force acts at the mass centre of the javelin, and hence determines fully the translational motion of the implement, and in which the pitching moment (M) fully determines the rotational

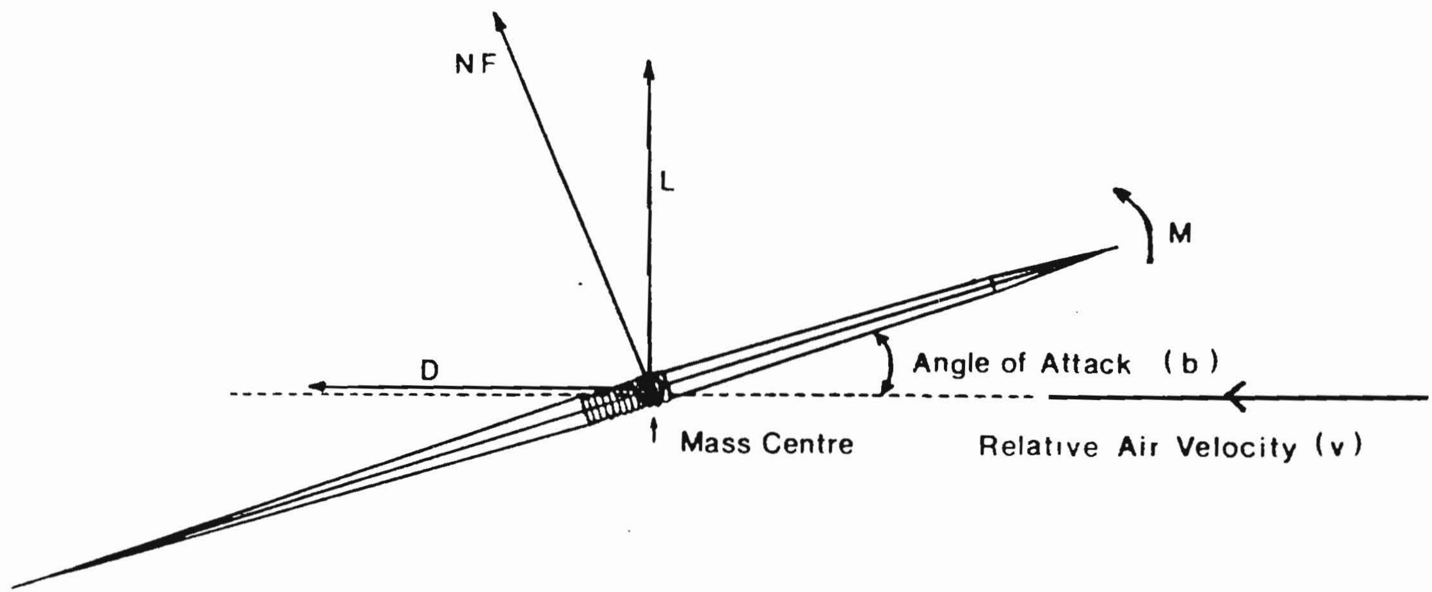

Fig. 2

motion of the javelin. The magnitude of this pitching moment is equal to the component of the aerodynamic force vector normal to the longitudinal axis of the javelin (NF) multiplied by the distance between the centres of mass and pressure. This distance for the new rules javelins is different from that for the old rules implement and the changed specification has reduced the possibility for designers to maximise planform area in front of the centre of mass.

These changes have particularly important consequences for the pitching moment characteristics of the javelin, as evidenced by figure 3, where the pitching moment for the new rules javelin is seen not to change sign, and is in fact negative for all positive angles of attack. This causes the javelin to pitch nose down from release till landing unless it is released with a negative angle of attack or the angle of attack becomes negative towards the end of flight (Best and Bartlett, 1987a). There is a considerable discrepancy between the measured pitching moment characteristics of Best and Bartlett, (1987c) on an Apollo javelin, and those reported by Terauds (1985) on a held javelin.

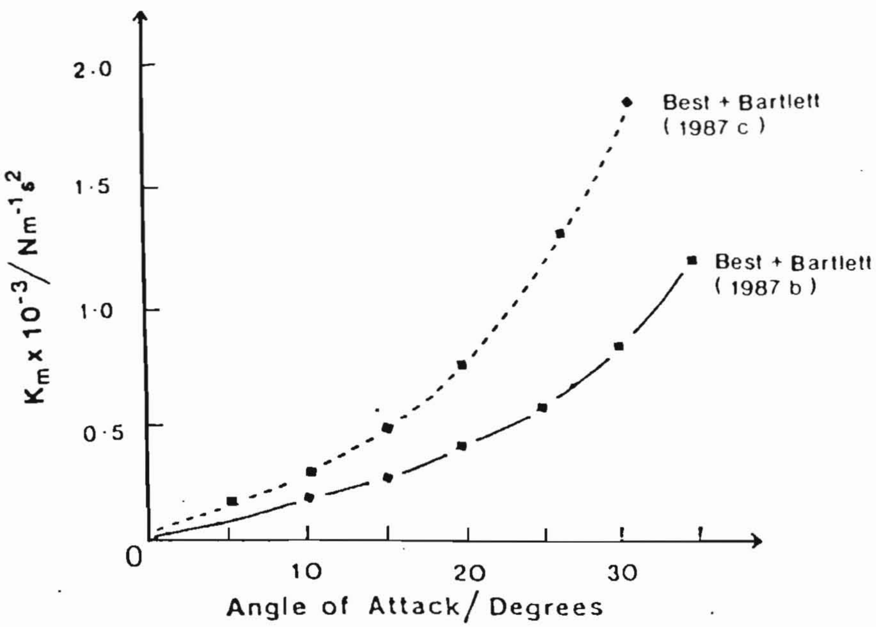

Fig. 3

The results of Best and Bartlett (1987c), (figure 4) show that the centre of pressure of the new rules Apollo Olympic javelin maintains a constant position $25^1/_2$ cm behind the mass centre. This contrasts with the results of Terauds (1972) for the old rules javelins, for which the centre of pressure moves either side of the mass centre depending on the angle of attack, as is indicated by the three equilibrium points in slide 5, at which the pitching moment is zero. This enabled the old rules javelins to generate

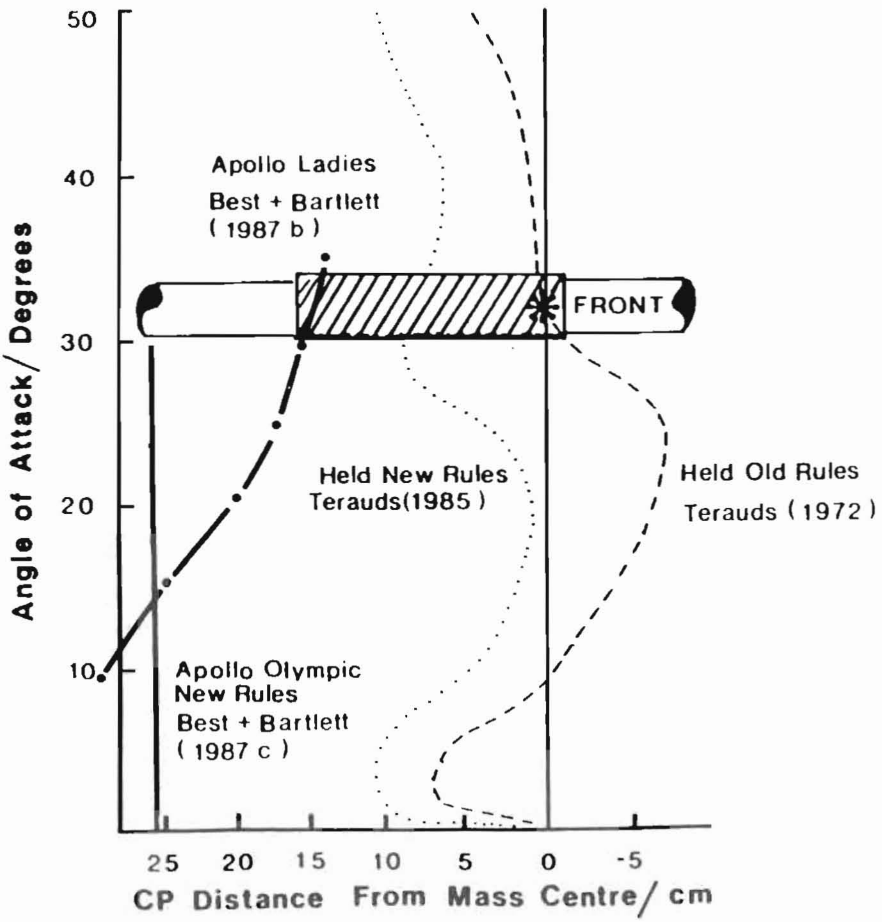

Fig. 4

sustained, large lift at an angle of attack of about 32° as the pitching moment acted to maintain that angle. However, the positive pitching moments between 10° and 32° produced pitching instability. The centre of pressure and pitching moment characteristics of the 1986 rules javelins appear to be the main cause of their range decrement, and this should be of great importance to manufacturers. The centre of pressure of the Apollo Aerodyne DR ladies' javelin is also always behind the centre of mass, but is not a constant value (Best and Bartlett, 1987b). Unlike the old rules men's javelins (Terauds, 1972), there are no positive angles of attack for which the pitching moment is positive for either the new rules or ladies' implements.

Terauds (1985) stated that the held new rules javelin has greater lift forces at a given angle of attack than the old implements (figure 5), but that this beneficial effect is offset by its tendency to fly at lower angles of attack because of its negative pitching moment characteristics, thus generating less lipt during flight. This is again not borne out by the wind

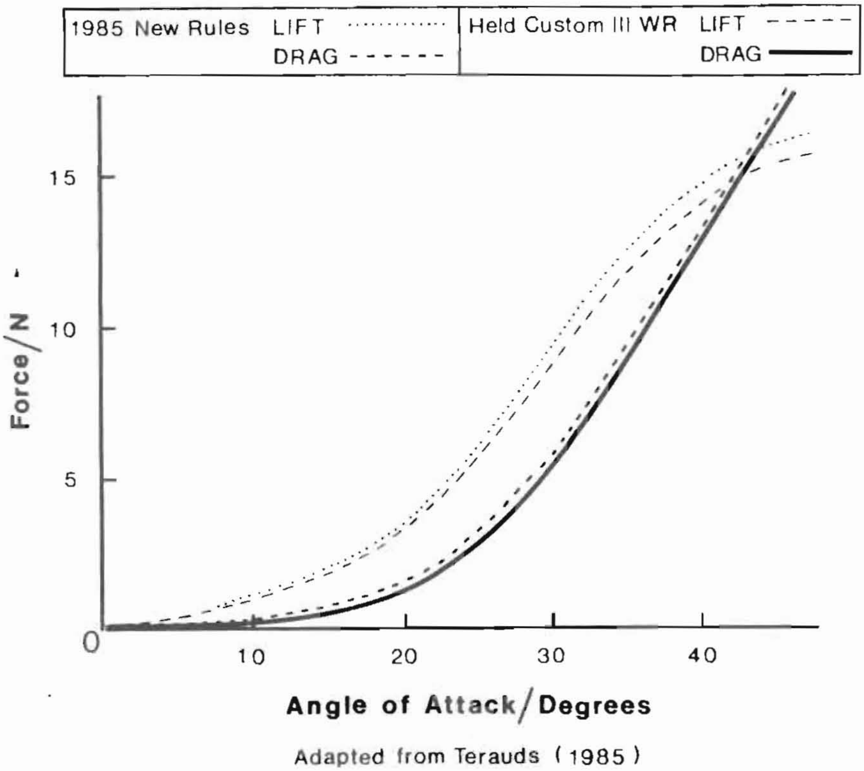

Fig. 5

tunnel results of Best and Bartlett (1987c), which show a lift coefficient (figure 6) 30% less on the Apollo javelin than that reported by Terauds (1985) on the held javelin with the lift force on the new rules Apollo javelin being somewhat less than on the old implements.

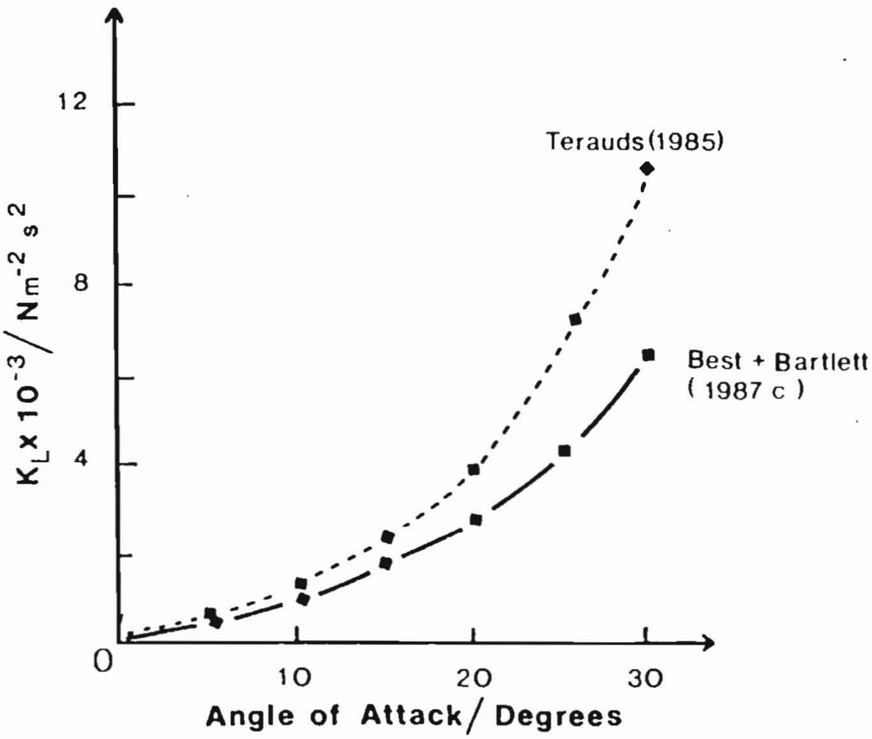

Fig. 6

Unaware, at the time, that Terauds' (1985) new rules javelin data was based on transonic range tests on a held javelin, Best and Bartlett (1985c) carried out extensive calibration and equipment checks and repeated retests to account for the discrepancies between these two sets of data, but found no systematic error in either their results or any of their procedures. Suspecting then that the discrepancies between their data and that of Terauds (1985) might be owing to differences between javelins, Best and Bartlett (1987c) measured the aerodynamic forces and pitching moments on two other new rules javelins, the Sandvik Champion N and the Held Mk IV, at their minimum error angle (30°). The computed centre of pressure positions for the three implements did not differ by more than 2 cm.

The overall planform area of the ladies' javelin suggests that its lift, drag and pitching moments will be less than those of the new men's javelin, if there is no substantial difference in the aerodynamic coefficients, as confirmed by Best and Bartlett (1987b). The ratio of the drag force on the ladies' to that on the new men's javelins is greater than the corresponding lift and pitching moment ratios. Hence the lift/drag ratio is smaller for the ladies' implement, but is still within the range reported for bodies of high fineness ratio (Schlichting and Truckenbrodt, 1979). This low lift to drag ratio helps to explain why the distances thrown in the ladies' event are below their ballistic range as is now the case for the new rules men's javelins (Best and Bartlett 1987b). The results of these authors also lend no support to Terauds (1985) statement that the new rules may be sufficiently flexible to permit the design of a new «gliding» javelin, although there appears to be some scope for improvement in the distribution of planform area for the ladies' javelin.

The lift and drag forces and pitching moments are quadratic functions of speed if the force and pitching moment coefficients are constant. This quadratic relationship (figure 7) was established for the new rules men's

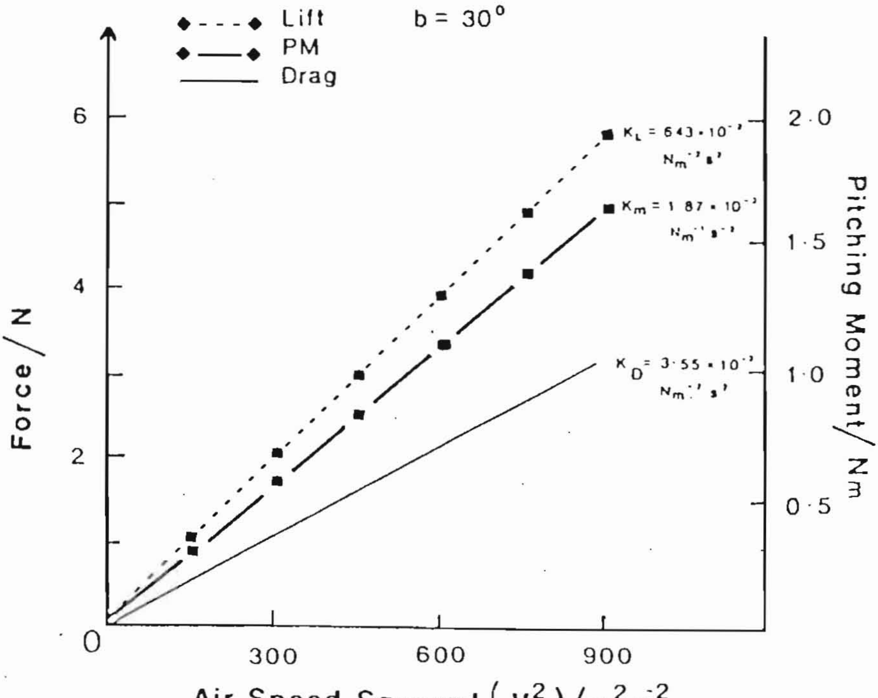

Fig. 7

javelin to a high degree of correlation ($r>0.98$), a finding confirmed for the ladies' implement, but with different aerodynamic coefficients (Best and Bartlett, 1987b,c). These authors found that the aerodynamic coefficients for the new rules men's javelins were exponentially related to the angle of attack (<0.01), and that similar shaped curves applied to the ladies' implement. These results give similar shaped relationships to those of Schlichting and Truckenbrodt (1979) for the lift and drag coefficients. However the exponential pitching moment relationship differs both from the linear relationship of Schlichting and Truckenbrodt (1979) and the findings of Terauds (1972), but was found to be highly reproducible (Best and Bartlett, 1987c).

Terauds (1985) suggested that the effect of the grip on the flight characteristics of the javelin is not significant since the grip has little influence on the pitching moment of the javelin. This is a surprising comment as the grip would obviously affect the airflow (e.g. Ericsson and Reding, 1985). However, the grip will have little, if any, effect on the javelin's important centre of pressure characteristics, because of its closeness to the centre of mass. It is the aerodynamic forces furthest away from the centre of mass that have the greatest effect because of the larger relative moment arm, an important consideration in terms of nose and tail design.

Genxing et al. (1986) found that the primary vortices around sharp, slender bodies of revolution (e.g. the nose of the javelin) were symmetrical at a speed of 30 m s^{-1} and at angles of attack of less than 30°. However, for higher angles of attack, they reported that the primary vortices became asymmetrical, generating side forces that would tend to make such a body yaw. Terauds (1985) indicated that the old rules Sandvik Custom 110 m javelin tended to stall and yaw at an angle of attack of 32° and above, and the same author (1972) reported that Sandvik javelins changed course during flight, landing up to 15 m to the side of the original path of flight. These results could be attributed to the asymmetrical vortices found by Genxing et al. (1986), which may also affect other designs of javelin, emphasising the importance of the air flow around the nose of the javelin and the relatively large effects small forces have in this area.

A common misconception (e.g. Ganslen, 1960) is that all positive lift is generated in front of the javelin's mass centre and that negative or zero lift is generated behind this point. Ganslen (1967) asserted that the distribution of the javelin's surface area is the prime determinant of its centre of pressure position. This is true since the distribution of surface area is determined from the shape, but the phenomenon is far more complicated than simply 'how much is in front and how much behind'. The distribution of the planform area also affects the position of the centre of pressure. Differences between javelins in these respects are important for both throwers and manufacturers such that, for identical release and atmospheric conditions, two different makes of javelin might differ by more than 10 m in range (Terauds, 1972). The importance of choosing a javelin to suit the thrower's range capability (or, more accurately, the javelin speed relative to the air at release) is thus highlighted.

EFFECTS OF WIND VELOCITY

Despite being neither measured nor even considered in the majority of studies reported in the literature, the wind velocity appears to be a crucial factor in determining the flight of the javelin. The aerodynamic characteristics of the javelin are dependent on the magnitude and direction of its velocity vector relative to the air, not to the ground. The effect of a headwind at release is to increase the speed of the javelin relative to the air (figure 8) and to cause the angle of attack to be greater than the difference between the attitude angle and the release angle (figure 1). The reverse applies for a tailwind (figure 8). A thrower experiencing a headwind may often release the javelin with a slightly negative «uncorrected» angle of attack but the headwind will result in a slightly positive angle of attack and hence positive lift. Of the experimental studies of javelin throws, only that of Miller and Munro (1983) has considered wind conditions. Unfortunately, they erred in the sign of the correction term which they would have applied had they known the wind speed.

The wind speed relative to the ground is not constant throughout flight, as recognised by Ganslen (1960) who suggested that «because the javelin is thrown relatively close to the ground, it is subject to turbulent air conditions in many stadia». The region of the atmosphere which is of most interest here is that below 50 m, the «surface boundary layer» (McIntosh and Thom, 1981), in which the wind speed decreases from its free stream value to zero at the ground through an essentially turbulent boundary layer (figure 9), with a laminar sub-layer very close to the ground. A totally laminar boundary layer is seldom, if ever, found over extensive natural surfaces. Although these changes in wind speed with

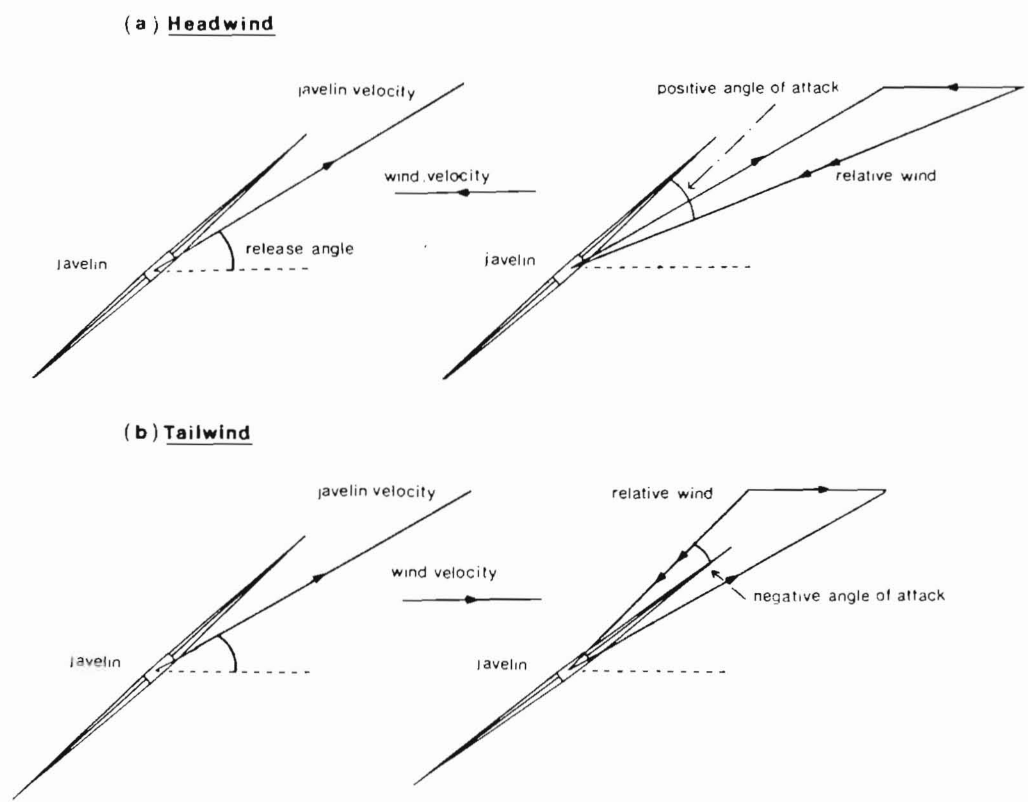
(a) Headwind
javelin velocity
wind velocity
release angle
javelin
positive angle of attack
relative wind
javelin
(b) Tailwind
javelin velocity
wind velocity
javelin
relative wind
negative angle of attack
javelin

Fig. 8

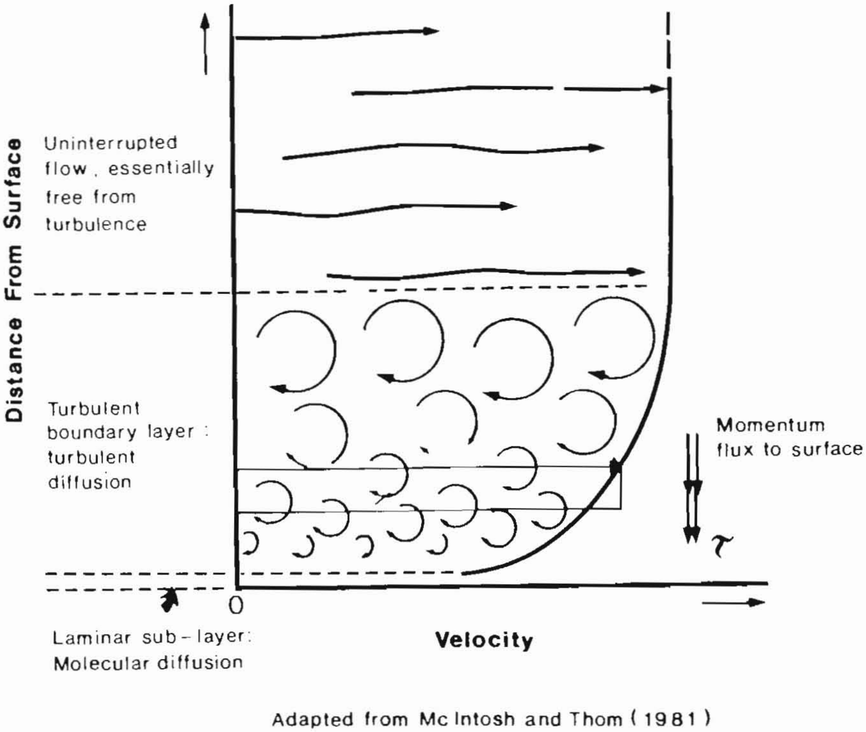

Fig. 9

altitude might appear important to the javelin thrower, it should be noted that they assume an infinite plane boundary, which is not the case in a large stadium, where other factors will complicate this phenomenon.

The effects of sidewind suggest that the athlete should «throw to the side of the sector towards the wind» (Terauds, 1985) as it was considered beneficial for an athlete to throw the old rules men's javelin into the wind. However, Best and Bartlett (1987b,c) have reported that this latter statement does not apply to either the ladies' or the new rules men's javelins. A sidewind acting on a spinning javelin will generate a Magnus force, the direction of which is perpendicular to the plane containing the spin and wind velocity vectors. A right handed thrower will release the javelin such that a sidewind blowing from left to right will generate positive Magnus lift, whilst one from right to left will cause negative lift. The relative importance of these forces, and how they are affected by the athlete's grip, has not been assessed.

On very gusty days, there is an observed tendency for a greater proportion of throws to stall adn/or yaw. The angles and pitch rate at release become more crucial, as the relative aerodynamic contribution to range increases, thus making control of the javelin more difficult but more important. Under such conditions, a shorter, more controlled run-up (5 or 7 strides) often results in the best throw. Optimum values of all of the javelin angles at release decrease in a headwind, hence it is possible that releasing the javelin with angles that correspond to still air optima will lead to a stall in a gusty headwind. There is less margin for error when throwing into a headwind whilst with a tailwind the release speed increases in importance as any aerodynamic contribution to range decreases.

As mentioned previously, when throwing new rules javelins, it has become apparent that throwers prefer tailwinds as against the headwinds that were favoured with the old rules javelins. The reduced javelin speed relative to the air (figure 8) leads to a lower pitching moment in a tailwind at a given angle of attack. This partially offsets the nose down effect, now a very important factor in new rules javelin throwing.

JAVELIN FLUTTER AND SPIN

There is little quantitative information available for a thorough analysis of the effects that flutter of the javelin has on its flight, at least partly attributable to the sheer complexity of the problem, although the vibrations of the implement are often mentioned (e.g. Ganslen, 1967; Terauds, 1972). It is not entirely clear whether this flutter is a result of transverse vibrations of the javelin shaft or the precession of the longitudinal, spin axis or a combination of the two. Vibration of the javelin is initiated by the transverse energy transfer to the javelin at release by pull down, and occurs at one of the lower natural frequencies of the javelin. The acceleration of the javelin during the delivery stride has a mean value of about 40 times gravitational acceleration and the large forces generating these accelerations create the transverse vibrations observed from high speed film and video recordings of javelin release and flight (e.g. Hubbard and Alaways, 1987b). These authors showed vibration amplitude peaks at 24 Hz, the fundamental frequency of transverse javelin vibrations predicted from finite element analysis, and in close agreement with results reported by Terauds (1985).

The amplitude of the vibrations generated will depend on the stiffness, mass and geometry of the javelin shaft. The persistence or otherwise of these transverse vibrations into flight will depend on the damping characteristics of the javelin. There appear to be considerable differences between javelins in these respects with some new rules implements being particularly prone to this problem, which results in increased drag and reduced lift.

The precession of the longitudinal, spin axis of the javelin was mentioned by Ganslen (1960) but otherwise has received little consideration in the literature. The rotational dynamics of the javelin can best be explained with respect to a system of orthogonal coordinates which moves and rotates with the javelin but around which the javelin spins. For such a rotating triad, there is an inevitable cross coupling of moments and angular momentum changes such that a moment in the vertical plane, due to the lift and drag forces in that plane, will result in a precession of the spin axis. Like vibration, this will result in an increased drag and reduced lift. A mean spin rate of 22.1 Hz was reported for four throwers by Terauds (1978), and such spin rates may affect the range and alter the optimal release conditions proposed by e.g. Hubbard (1984a,b). Whilst Hay (1985) considers spin «to have a beneficial stabilising effect», the centroidal moment of inertia about the long axis is less than 0.1% of that about the short axis so that the javelin's spinning angular momentum is very small, suggesting that its effect on javelin flight may be minimal. The importance of flutter appears to be far greater for new rules javelins and is an important consideration for manufacturers.

CONCLUSIONS

This paper will, hopefully, have demonstrated some of the difficulties associated with accurately establishing the aerodynamics of javelin flight. It is difficult currently to assess the magnitude of the errors involved in assuming javelin flight to be adequately expressed by the equations of planar motion of a rigid body. Undoubtedly there is a need to conduct wind tunnel tests which more closely replicate the field conditions, although this presents considerable technical problems. An alternative approach might be to seek to establish the importance of factors such as the spin and vibrations of the javelin on the implement's aerodynamic characteristics, using computer simulations based on appropriate mathematical models. There is much research still to be done before a full understanding of javelin flight is achieved.

REFERENCES

Best, R. J. and Bartlett, R. M. (1987a). Computer flight simulation of the men's new rules javelin. Communication to the XIth conference of the International Society of Biomechanics, (Amsterdam).

Best, R. J. and Bartlett, R. M. (1987b) Ladies' javelin: aerodynamics, flight simulation and biomechanical considerations. Communication to the Fifth International Symposium of Biomechanics in Sports, (Athens).

Best, R. J. and Bartlett, R. M. (1987c) Aerodynamic characteristics of new rules javelins. Communication to the Institution of Mechanical Engineers Conference on Biomechanics in Sport, (Leeds).

Ericsson, L. E. and Reding, J. P. (1985). Dynamics of forebody flow separation and associated vortices. Journal of Aircraft 22, 329-335.

Ganslen, R. V. (1960). Aerodynamics of javelin flight. Unpublished Master's thesis, University of Arkansas.

Ganslen, R. V. (1967). Javelin aerodynamics. Track Technique 30, 940-943.

Genxing, R. V., Tzehsing, W. and Shixhong, T. (1986). Investigation of vortex patterns on slender bodies at high angles of attack. Journal of Aircraft 23, 321-325.

Hay, J. G. (1985). The Biomechanics of Sports Techniques. New York: Prentice-Hall.

Hubbard, M. (1984a). Optimal javelin trajectories. Journal of Biomechanics 17, 777-787.

Hubbard, M. (1984b). Javelin trajectory simulation and its use in coaching. Proceedings of the Second International Symposium of Biomechanics in Sports. Del Mar: Academic Publishers.

Hubbard, M. and Alaways, L. W. (1987a). Optimum release conditions for the new rules javelin. International Journal of Sports Biomechanics 3.

Hubbard, M. and Alaways, L. W. (1987b). Implementation of a javelin trajectory instrumentation system. Communication to the Fifth International Symposium of Biomechanics in Sports, (Athens).

McCormick, B. W. (1979). Aerodynamics, Aeronautics and Flight Mechanics. New York: John Wiley and Sons.

McIntosh, D. H. and Thom, A. S. (1981). Essentials of Meteorology. London: Taylor and Francis.

Miller, D. I. and Munro, C. F. (1983). Javelin position and velocity patterns during final foot plant preceding release. Journal of Human Movement Studies 9, 1-20.

Schlichting, H. and Truckenbrodt, E. (1979). Aerodynamics of the Aeroplane. New York: McGraw-Hill.

Terauds, J. (1972). A comparative analysis of the aerodynamic and ballistic characteristics of competition javelins. Unpublished doctoral dissertation, University of Maryland.

Terauds, J. (1978). Javelin release characteristics of U.S.A. and U.S.S.R. throwers- 1974. Track and Field Quarterly Review 78, 42.
Terauds, J. (1985). Biomechanics of the Javelin Throw. Del Mar: Academic Publishers.
Watman, M. (1986). World records in Europe. Athletics Weekly, September 27th, 5-10.