

## SHORT COMMUNICATION

# A CRITICAL ANALYSIS OF THE USE OF HIGH-SPEED FILM TO DETERMINE MAXIMUM ACCELERATIONS OF FISH

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High-speed cinematography is often employed in studies on fish swimming, particularly where performance is estimated (e.g. Wardle, 1975; Eaton *et al.* 1977; Webb, 1978*b*; Dorn *et al.* 1979; Videler, 1981). One commonly reported aspect of performance is the acceleration of fish during fast-starts (bursts of swimming from a standing start; e.g. Weihs, 1973; Webb, 1975, 1976, 1977, 1978*a,b*, 1982, 1983, 1986; Rand & Lauder, 1981). The present study is a critical examination of the use of cinematography to estimate the maximum acceleration of fish during fast-starts.

Accelerations must be derived from the distance–time data provided by the film. This is accomplished by employing statistical methods that generate the second differential of distance with respect to time. In his early studies, Webb (1975, 1976) differentiated the empirical equation derived from a simple linear regression, calculated for the distance–time data. Later studies (Webb, 1977, 1978*a,b*, 1982) employed a more sophisticated five-point moving regression method which was found to have significantly greater accuracy (Webb, 1977). This method provides instantaneous accelerations as opposed to averages, allowing for the peak performance during fast-starts to be reported as maximum acceleration.

The error involved in performing the differentiations has not been quantitatively analysed. Webb (1975) argued that the error in calculating instantaneous accelerations as well as the over-smoothing error (the tendency for successive differentiations to smooth high-frequency variations in acceleration) were small when the simple linear regression method was employed. As stated previously, this method was later abandoned for a more accurate one (Webb, 1977) and no further reference to the error inherent in film analysis was made. Other sources of error, such as the condition of the fish and the temperature and salinity of the water, have been suggested (Blaxter, 1969). These are deemed easily controllable and are not considered here.

Two independent sources of error are inherent in film analyses; that involved in measuring the distance moved from frame to frame and that related to the sampling frequency (in this case, film speed). The effects of each are summed to determine total error.

**Key words:** fish fast-starts, error, film, maximum acceleration.

Films provide accurate distance–time data, but their ability to provide instantaneous accelerations is highly dependent on framing rate. All accelerations derived from film assume that acceleration is piecewise constant in time (Rayner & Aldridge, 1985). This averaging, or over-smoothing, will be referred to in this communication as sampling frequency error (SFE). As the interval between frames lessens, so does the difference between frame-averaged and actual instantaneous accelerations. This results in a lower SFE. The exact relationship between film speed and SFE has not been previously reported, but some problems arising from low sampling rates have been addressed (Eaton *et al.* 1977).

Sampling rates in the earlier studies on fast-starts were of the order of 60 Hz. Webb (1975, 1976) used film speeds of 64 Hz, which provided only five data points to calculate velocity and acceleration for a given fast-start. Later Webb (1977, 1978*a,b*, 1982) used film speeds of 250 Hz along with improved analysis techniques (discussed earlier) to obtain better estimates of instantaneous maximum accelerations. The SFE, however, could not be evaluated because actual instantaneous accelerations were not directly measured.

The error involved in measuring the distance moved from frame to frame will be referred to as measurement error (ME). The accuracy with which images on a screen can be converted to digital information will vary with the type of imaging system used and from person to person. The error should, however, remain relatively constant for the same individual using the same system. ME will also be affected by other forms of distortion, such as image blurring and parallax. These sources of error were found to be relatively small and are not considered here.

Fabrication of hypothetical acceleration–time data creates a controlled environment in which the effects of the sources of error can be explored. The acceleration curve (Fig. 1), hereafter referred to as 800norm, was created to simulate the rise-time and maximum acceleration typical of that recorded from an accelerometer implanted subcutaneously in a fish (Harper & Blake, 1989). The curve consists of acceleration data plotted every 0.00125 s (1/800 s) forming a unimodal, symmetrical acceleration profile. The time interval was selected to provide sufficient data points to describe accurately the unimodal curve.

Distance–time data were generated from the acceleration data by twice integrating with respect to time. This provided the cumulative distance moved at a sampling frequency of 800 Hz, thus simulating the type of information that is accurately recorded by film (i.e. distance–time data). As a control, these data were then converted to instantaneous distance–time information and twice differentiated with the moving regression method (Webb, 1977). Some over-smoothing of the already smooth data did occur, but comparison with 800norm indicated that this error was less than 1%.

The 800norm cumulative distance–time data were then used at progressively lower sampling frequencies to estimate SFE. This was done by taking every second distance–time point to simulate a film speed of 400 Hz, every fourth point for 200 Hz, etc. The resulting data sets were twice differentiated with the moving regression method and compared with 800norm.

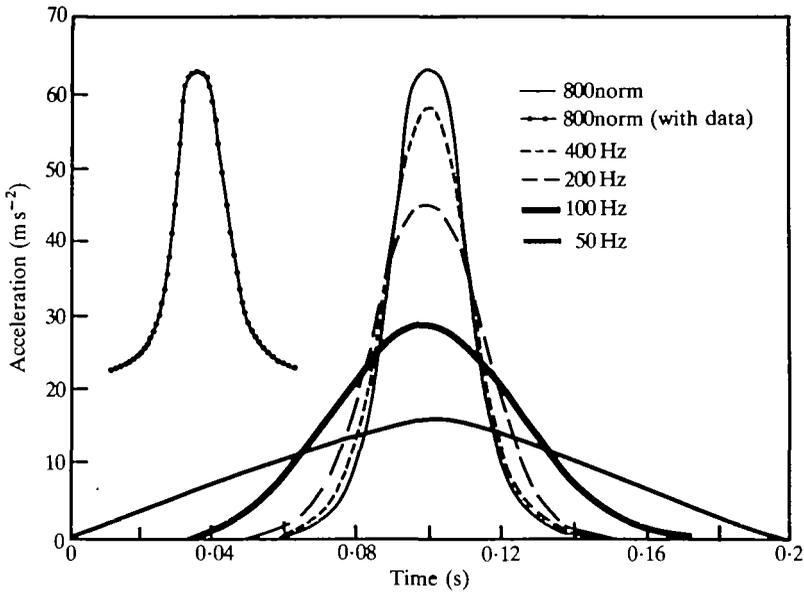


Fig. 1. Hypothetical acceleration–time plot (800norm) with traces simulating the same data sampled at frequencies of 400, 200, 100 and 50 Hz. A full description is given in the text.

The effects of the simulated reduction of film speed to 400, 200, 100 and 50 Hz are plotted in Fig. 1. Two major departures from 800norm become apparent: the maximum accelerations become progressively smaller and the curve becomes less peaked and broader.

SFE was determined using a simple method of comparison where the difference between the maximum acceleration of 800norm and the test case is presented as a percentage of the 800norm value. For example, the calculation for the test case at 400 Hz is:

$$\text{SFE} = \frac{|A_{800} - A_{400}|}{A_{800}} \times 100. \quad (1)$$

SFE for maximal accelerations is plotted against film speed in Fig. 2. The equation for this line was determined from a regression analysis to be:

$$\text{SFE} = 10^{(-0.00279\text{FS} + 2.019)}, \quad (2)$$

where FS is the film speed in Hz. Maximum acceleration ( $A_{max}$ ) is the chosen point of interest because this value is often reported in studies on fish fast-starts (e.g. Weihs, 1973; Webb, 1975, 1976, 1977, 1978a,b, 1983). It is also of biological relevance because it represents the maximum level of performance that can be employed during life-threatening situations. Fig. 2 shows that SFE increases exponentially with decreasing film speed. It should be noted that SFE will always cause underestimations of actual accelerations because of over-smoothing.

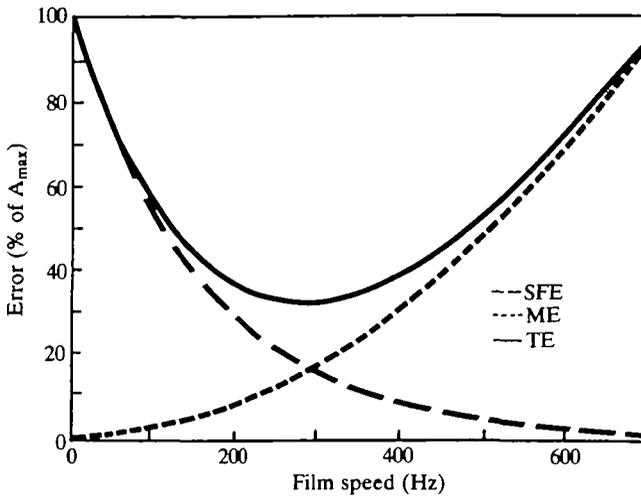


Fig. 2. Sampling frequency error (SFE), measurement error (ME) and total error (TE) as a percentage of the maximum acceleration rate ( $A_{\max}$ ) in Fig. 1. The errors are plotted against film speed.

The effect of random measurement error (ME) will be to over- or underestimate actual accelerations. ME arises from small mechanical and electrical imperfections in the camera and digitizing system. The camera of reference in this study (Locam model 51-0002) has a maximum error of  $\pm 1\%$ , translating to a fractional uncertainty of  $\pm 0.01$ . The error in the digitizing system (Photographic Analysis Ltd Projection Analysis Unit ZAE 76), determined by repeated relocations of the cursor to predetermined locations (thereby accounting for both human and system error), was found to be  $\pm 2\%$  in both the  $x$  and  $y$  directions. This may vary with the system used, but is unlikely to be less than  $2\%$ . Because the uncertainties in  $x$  and  $y$  are independent and random, the total error in determining any distance ( $\delta D$ ) is given by (Taylor, 1982):

$$\delta D = \pm \sqrt{(\delta x)^2 + (\delta y)^2}, \quad (3)$$

where  $\delta x$  and  $\delta y$  are the uncertainties in  $x$  and  $y$ , respectively. This gives a total distance uncertainty of  $2.83\%$ . Since acceleration is determined by twice differentiating the distance data with respect to time, the distance and time uncertainty will be propagated and smoothed during this procedure.

Because ME arises during digitizing of each frame of the film, it will also increase with film speed. As film speed increases, the distance moved per frame decreases, so the digitizing error becomes a greater proportion of the measured distance. To present ME as a proportion of acceleration, it is necessary to multiply the fractional uncertainty for acceleration by film speed squared, since distance is twice divided by time in the double differentiation. Therefore, ME for the acceleration-time data, at any film speed, is given by:

$$ME = 0.000125(FS)^2. \quad (4)$$

This gives an absolute value for the uncertainty in derived accelerations. To determine actual ME values, the magnification of the image on the digitizing tablet must be considered. For example, if the image on the tablet is actual size, then every centimetre measured will correspond to 1 cm of movement and the uncertainty will be given directly from equation 4 in units of  $\text{m s}^{-2}$  (e.g. at a film speed of 200 Hz the uncertainty in acceleration will be  $\pm 5.0 \text{ m s}^{-2}$ ). To present this in the same way as SFE, ME must be calculated as a percentage of  $A_{\text{max}}$ . However, because ME is constant for any combination of film speed (FS in Hz) and magnification, presenting it in this way makes ME dependent on  $A_{\text{max}}$ :

$$\text{ME} = \frac{100^{[\log(\text{FS})]}}{800A_{\text{max}}} \quad (5)$$

Increasing the image size has the same effect on ME as decreasing the film speed in equal proportion. For example, if the film speed is halved, the fish will move twice as far on the tablet, from one frame to the next. It is easily shown that the same will occur if image size is doubled. Likewise, if image size is reduced, the effect will be similar to increasing the film speed. In this way, an allowance for departures from actual-size magnifications can be made by adjusting film speed. ME is calculated using the  $A_{\text{max}}$  from the SFE analysis and is plotted against film speed on Fig. 2, demonstrating that ME increases exponentially with film speed.

The total error (TE) results from the additive effects of SFE and ME (Fig. 2). Because SFE is inversely proportional to film speed and ME is proportional to it, the curve for total error is U-shaped, resulting in an optimal film speed for minimum error. The optimal speed predicted for the hypothetical example, 800norm, at actual image size, is approximately 280 Hz (Fig. 2). Note that the minimum total error at this film speed is about 33%. Subsequent optima can be obtained for varying image magnifications. Fig. 3 shows the optimal film speed and corresponding minimum error for (log)image magnifications ranging from  $\times 0.05$  to  $\times 20$ .

Clearly, there is a need to consider sources of error when deriving accelerations from film. This is shown to be particularly important when using a reduced image size (Fig. 3). Because image magnification has not been reported in the literature, it is not possible to estimate the error for the maximum accelerations reported. However, Fig. 2 suggests that the accelerations derived from films taken at less than 100 Hz are unreliable. This side of the total error curve is driven by SFE, which is dependent on neither the magnification nor the magnitude of acceleration, as discussed earlier.

Many adult fish are large enough to accommodate implantations of accelerometers. Therefore, the use of film to estimate maximum fast-start accelerations must be questioned. Even when distance-time data are statistically smoothed before each differentiation, it is still common for small-amplitude noise in the distance-time data to be amplified and distort the acceleration-time trace substantially, rendering it useless (Rayner & Aldridge, 1985). The principal assumption made when employing these statistical methods is that there are no

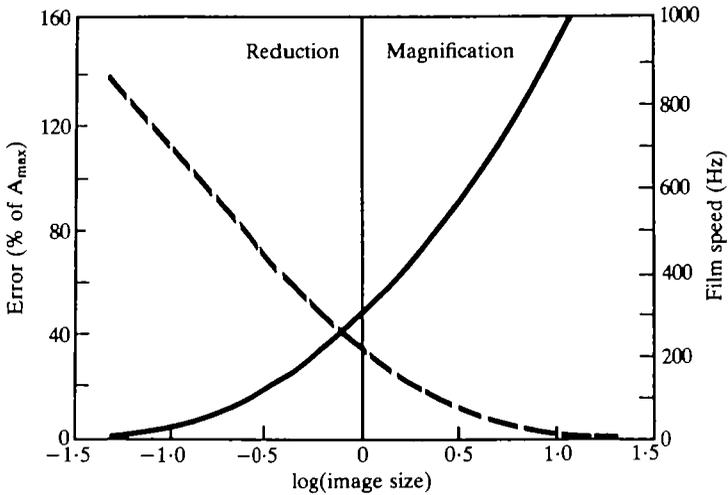


Fig. 3. Minimum error (dashed line) and optimal film speed (solid line) for a range of image sizes. The left side of the figure represents image reductions and the right side image magnifications.

sudden changes in force and therefore acceleration (Lanczos, 1956). With reference to fast-starts in fish, this is a rash assumption; rates of change of acceleration during fish fast-starts are sometimes of the order of  $100 \text{ m s}^{-2}$  in about  $0.02 \text{ s}$ .

Miniature accelerometers make direct measurements of acceleration practical and reliable (Harper & Blake, 1989). For very small animals (e.g. insects, larval fish, etc.), or those that cannot be readily tethered (e.g. birds), film studies remain one of the few practical methods available. Film also allows kinematic analyses of accelerative events, so it should be used where possible.

When film must be used, error can be limited by maximizing image magnification (Fig. 3) and selecting the corresponding optimal film speed. Fig. 2 suggests that simply increasing film speeds does not necessarily improve the reliability of the derived accelerations, because ME increases exponentially with film speed. Webb (1977, 1978*a,b*, 1982) employed film speeds as high as 250 Hz. At this sampling rate, the minimum total error for images of actual size is of the order of 40% (Fig. 2). At extreme magnification ( $\times 20$ ) and very high film speeds ( $> 1000 \text{ Hz}$ ), the practical lower limit of total error approaches zero (Fig. 3). Modern high-speed ciné cameras can run at speeds of the order of 10 000–12 000 Hz, so the limiting factor in reducing this error is the magnification of the image which, in turn, is partly dependent on the size of the digitizing tablet. The digitizing tablet should be as large as practically possible.

Magnification is also limited by the behaviour of the specimen. If the direction of the fast-start is unpredictable (e.g. startle response of fish) space must be left on all sides of the specimen in the camera viewfinder. If the behaviour is more

predictable, as in predation studies, the camera should be 'zoomed-in' on the specimen, leaving space only in the predicted direction of motion.

This communication has demonstrated that errors due to sampling frequency and measurement act independently, but can be summed (using equations 2 and 5) to determine the total error arising. Fig. 3 is particularly useful in that it gives optimal film speeds for known image magnifications, which can be employed to limit the error associated with film-derived accelerations.

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### References

- BLAXTER, J. H. S. (1969). Swimming speeds of fish. *FAO (Food and Agricultural Organization of the United Nations) Fisheries* **62**, 69–100.
- DORN, P., JOHNSON, L. & DARBY, C. (1979). The swimming performance of nine species of common California inshore fishes. *Trans. Am. Fish. Soc.* **108**, 366–372.
- EATON, R. C., BOMBARDIERI, R. A. & MEYER, D. L. (1977). The Mauthner-initiated startle response in teleost fish. *J. exp. Biol.* **66**, 65–81.
- HARPER, D. G. & BLAKE, R. W. (1989). On the error involved in high-speed film when used to evaluate maximum accelerations of fish. *Can. J. Zool.* (in press).
- LANCZOS, C. (1956). *Applied Analysis*. Englewood Cliffs, New Jersey: Prentice Hall.
- RAND, D. M. & LAUDER, G. V. (1981). Prey capture in the chain pickerel, *Esox niger*: correlations between feeding and locomotor behaviour. *Can. J. Zool.* **59**, 1072–1078.
- RAYNER, J. M. V. & ALDRIDGE, H. D. J. N. (1985). Three-dimensional reconstruction of animal flight paths and the turning flight of microchiropteran bats. *J. exp. Biol.* **118**, 247–265.
- TAYLOR, J. R. (1982). *An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. Mill Valley, CA: University Science Books.
- VIDELER, J. J. (1981). Swimming movements, body structure, and propulsion in cod (*Gadus morhua*). In *Vertebrate Locomotion* (ed. M. H. Day). *Symp. Zool. Soc., Lond.* **48**, 1–27. London: Academic Press.
- WARDLE, C. S. (1975). Limit of fish swimming speed. *Nature, Lond.* **255**, 725–727.
- WEBB, P. W. (1975). Acceleration performance of rainbow trout *Salmo gairdneri* and green sunfish *Lepomis cyanellus*. *J. exp. Biol.* **63**, 451–465.
- WEBB, P. W. (1976). The effect of size on the fast-start performance of rainbow trout *Salmo gairdneri*, and a consideration of piscivorous predator–prey interactions. *J. exp. Biol.* **65**, 157–177.
- WEBB, P. W. (1977). Effects of median-fin amputation on fast-start performance of rainbow trout (*Salmo gairdneri*). *J. exp. Biol.* **68**, 123–135.
- WEBB, P. W. (1978a). Temperature effects on acceleration of rainbow trout *Salmo gairdneri*. *J. Fish Res. Bd Can.* **35**, 1417–1422.
- WEBB, P. W. (1978b). Fast-start performance and body form in seven species of teleost fish. *J. exp. Biol.* **74**, 211–226.
- WEBB, P. W. (1982). Fast-start resistance of trout. *J. exp. Biol.* **96**, 93–106.
- WEBB, P. W. (1983). Speed, acceleration, and manoeuvrability of two teleost fishes. *J. exp. Biol.* **102**, 115–122.
- WEBB, P. W. (1986). Effect of body form and response threshold on the vulnerability of four species of teleost prey attacked by largemouth bass (*Micropterus salmoides*). *Can. J. Fish. aquat. Sci.* **43**, 763–771.
- WEIHS, D. (1973). The mechanism of rapid starting of slender fish. *Biorheology* **10**, 343–350.

