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A Note on the Deck Landing Velocities of Helicopters

by

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A NOTE ON THE DECK LANDING VELOCITIES OF HELICOPTERS

by

M.A.P. Willmer

SUMMARY

A theory has been developed to act as a guide in the interpretation of experimental results of the landing velocities of helicopters on small ships at sea. It has been shown that the concept of a normally distributed hover height together with a linear rate of decay of lift is satisfactory. A comparison has been made with results obtained from the Rolling Platform at Bedford and the agreement has been found to be quite good both for roll angles of 3 and 5 degrees. The theory has been extended to take into account the pitching motion of a ship with reasonable success.

Replaces Tech Note Naval 56 - A.R.C. 25288

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1 INTRODUCTION

In November 1959 some 270 landings of a Westland P531 helicopter onto a platform aboard the frigate H.M.S. Undaunted[1] were photographed in order to measure the contact velocities. Some idea of the rate of descent distribution was obtained but it proved to be virtually impossible to deduce very much about the frequency of the higher velocities as the number of readings available formed too small a sample. Such questions as 'at what velocity is there a one-in a thousand chance of it being exceeded' cannot be answered with any confidence for there is no theory at present which can act as a guide. In this respect, the situation is completely different from that of the landing of fixed wing aircraft aboard carrier at sea. There, it is possible to represent the frequency distribution by a normal curve and the effects of the pitching and rolling of the ship can be estimated easily. It is unfortunate that there are no grounds for continuing with this assumption when dealing with helicopter landings.

The differences arise because of the nature of the problems. In the fixed wing case, the pilot is trying to hold a steady rate of descent and it is not surprising therefore that, if the deck is stationary, a normal distribution of landing velocities will result. If the ship happens to be pitching, the pilot has virtually no control over the angle of the deck and the extra velocity due to the pitching at touchdown. An estimate of the effect therefore can be obtained without much difficulty because the randomness simplifies the mathematical treatment.

However, these factors, which simplify so much the theoretical work for the fixed wing case, do not apply when helicopters are considered. Now the pilot can use the controls to follow the motion of the ship as well as being able to lower the aircraft on to the deck as delicately as his ability will allow.

This present Note represents a first look at the new situation; an attempt has been made to develop a guide so as to be able to interpret the statistical data with greater confidence. As a starting point, it is assumed that the pilot will hover over the deck before attempting a landing. A theory is developed using the assumption that the distribution of these hover heights is normal and that the rate of decay of lift during the descent is linear with time. The mean hover height, the standard deviation and the rate of decay of lift will all depend upon the conditions appertaining at the time of the landing. For instance, on a calm day with little wind and ship motion a lower initial hover height and a considerably different distribution would be expected than for a case where the ship is pitching and rolling.

Using the rolling platform at R.A.E. (Bedford) and a Whirlwind helicopter, some six hundred landing velocities were measured at 3 or 5 degrees of roll. In order to examine the behaviour of the helicopter during the landings, a large number of them were photographed well before the landing took place. It was expected that the increase from 3 to 5 degrees would be sufficient to show how the effect of increasing the difficulty of the task to be performed would influence the hover height and landing velocity distributions. These experimental results have been used to demonstrate the theory which has afterwards been developed to take into account the ship's pitching motion.

2 THE PLATFORM LANDINGS

Fig.1 shows the Whirlwind landing on the rolling platform at Bedford during a typical descent. The rolling platform is described in Ref.2. The figure also shows the outriggers which were fitted to the platform for safety purposes, should the aircraft tend to slide off. Also to be seen are the three rods, one at each rear wheel and one in front, for recording the aircraft motion just before and after touchdown. It was from the records obtained from the main wheels that the contact velocities were determined. They are shown in greater detail in Fig.2 and a typical record is given in Fig.3.

To record the motion of the helicopter during the period prior to touchdown, a camera was placed about 50 yards from the platform. From the resulting film the hover height could be determined.

The landings were performed at 3 and 5 degrees of roll, about 300 in each case and the tests lasted just over a week. The landings were mostly performed in batches of about 20 and nearly half the landings were photographed for hover heights. During the week of the tests the windspeed was usually between 10 and 20 knots.

3 THE THEORY FOR A ROLLING DECK

The equation of motion for a helicopter descending onto a rolling deck is

$$M\ddot{s} = Mg - L \tag{1}$$

with L being the lift produced by the rotor and $\ddot{s}$ the downward acceleration and s is measured from the mean position, see Fig.4. If the decay in lift is linear with time, L can be represented by

$$L = Mg(1 - \lambda t) \tag{2}$$

so that at time t = 0 the helicopter would be in the hover. If there is no initial velocity, the relationship between the velocity of descent and the distance fallen can be shown to be

$$\dot{s}^3 = \frac{9}{2} g\lambda s^2 \quad . \tag{3}$$

Now if it is assumed that the distribution of hover heights is normal (μ_s, σ_s) the probability that s lies between s and $s + \delta s$ is proportional to

$\frac{1}{\sigma_s \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{s-\mu_s}{\sigma_s}\right)^2} ds$. As it is impossible for the hover heights to be negative, where the constant of proportionality, K, is given by

$$1 = \int_0^\infty \frac{K}{\sigma_s \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{s-\mu_s}{\sigma_s}\right)^2} ds \tag{4}$$

i.e.

$$K = \frac{1}{0.5 + \Phi(\mu_s/\sigma_s)} \tag{5}$$

where

$$\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{1}{2}t^2} dt \tag{6}$$

If it is assumed that the pilot attempts to land the helicopter when the deck is in the mean position then the probability distribution of the first wheel contact velocities is given approximately by

$$\varphi_1(\dot{s}) = \frac{K\dot{s}^{\frac{1}{2}}}{2\sigma_s \sqrt{\pi g \lambda}} \exp\left\{- \frac{1}{2\sigma_s^2}\left[\frac{2}{9g\lambda}\dot{s}^3 - \frac{2\mu_s}{3}\sqrt{\frac{2}{g\lambda}}\,\dot{s}^{3/2} + \mu_s^2\right]\right\}. \tag{7}$$

In practice, it is to be expected that because of the presence of the deck the normal distribution assumed above will be skewed. The effect of this skewness will depend upon the values of μ_s and σ_s; however the normal curve is thought to be a sufficiently good first approximation.

The estimation of the velocity of contact of the second wheel is extremely difficult; it will depend upon such factors as the pilot's control movements, the rate of lift decay and the angle of deck and rolling velocity at the contact of the first wheel.

However if it is assumed that the lift is equal to the weight, no initial rate of roll, that the motion of the first wheel has come to rest so that the aircraft can be considered to pivot about the point of contact and that the angle of roll is sufficiently large for the motion to become established, it can be shown that the velocity of contact of the second wheel is given by the equation,

$$\dot{s}_2 = \frac{2a^2 \dot{s}_1}{1 + a^2} \tag{8}$$

where

$$a = \bar{\ell}/\bar{k} \tag{9}$$

and $\bar{k}$ = radius of gyration of the aircraft in roll

$\bar{\ell}$ = semi distance between wheels.

The effect of the lift decay should not be significant as only a small amount of the lift is expected to be lost from the rotor and the initial rate of roll is also expected to be negligible. Of the other factors concerned so little is at present known that, in order to progress further, it is necessary to accept equation (8) and compare the results obtained with those of experiment. Thus the resulting probability distribution of the contact velocities of the second wheel can be shown to be

$$\varphi_2(\dot{s})$$

$$= \frac{K}{2\sigma_s \sqrt{\pi g\lambda}} \left(\frac{1+a^2}{2a^2}\right)^{3/2} \dot{s}^{\frac{1}{2}} \exp\left\{-\frac{1}{2\sigma_s^2}\left[\frac{2}{9g\lambda}\left(\frac{1+a^2}{2a^2}\right)^3 \dot{s}^3 - \frac{2\mu_s}{3}\sqrt{\frac{2}{g\lambda}}\left(\frac{1+a^2}{2a^2}\right)^{3/2} \dot{s}^{3/2} + \mu_s^2\right]\right\} \quad \ldots (10)$$

and the probability distribution for the velocity of contact of both wheels is given by the average of $\varphi_1(\dot{s}) \propto \varphi_2(\dot{s})$.

Although these probability distributions are very interesting, it is often more important in practice to determine the probability that a certain velocity will be exceeded. Hence, using the expression of equation (7), the probability that the velocity of contact of the first wheel exceeds q ft/sec is given by

$$\Pr(\dot{s} \geq q) = 1 - \int_0^q \varphi(\dot{s})\, d\dot{s} \qquad (11)$$

which reduces to

$$\Pr(\dot{s} \geq q) = 1 - K\left\{\Phi(|t_1|) - \Phi(|t_2|)\right\}; \quad t_2 < 0$$

$$= 1 - K\left\{\Phi(t_2) + \Phi(|t_1|)\right\}; \quad t_2 > 0 \qquad (12)$$

where

$$t_2 = \frac{\frac{1}{3}\sqrt{\frac{2}{g\lambda}}\, q^{3/2} - \mu_s}{\sigma_s}$$

and

$$t_1 = -\frac{\mu_s}{\sigma_s}. \qquad (13)$$

Similarly the probability that the velocity q ft/sec is exceeded when both wheels are considered is given by

$$\Pr(\dot{s} \geq q) = 1 - \frac{K}{2}(A + A') \tag{14}$$

where

$$\begin{aligned}
A &= \Phi(t_2) + \Phi(|t_1|) \quad t_2 > 0 \\
A' &= \Phi(t_2') + \Phi(|t_1'|) \quad t_2' > 0 \\
A &= \Phi(|t_1|) - \Phi(|t_2|) \quad t_2 < 0 \\
A' &= \Phi(|t_1'|) - \Phi(|t_2'|) \quad t_2' < 0
\end{aligned} \tag{15}$$

and

$$t_2' = \frac{\frac{1}{3}\sqrt{\frac{2}{g\lambda}}\left(\frac{1+a^2}{2a^2}\right)^{3/2} q^{3/2} - \mu_s}{\sigma_s}$$

$$t_1' = -\frac{\mu_s}{\sigma_s} \tag{16}$$

and t_2 and t_1 are given by equation (13).

Fig.5 shows the result for the three degrees of roll case using the experimental values for the parameters involved, and where the hover heights were determined from the photographs. During the course of the film analysis, it became apparent that the hover height was extremely difficult to estimate. Although the pilot meant to hover above the deck before descending in actual fact he only rarely achieved a stationary condition. It was found necessary to define the hover as a period in which the vertical velocity was less than 0.25 ft/sec. The theory can be modified to take into account an initial velocity at the 'hover height'; if at $t = 0$ there is an initial velocity of $\dot{s}_0$ ft/sec the relationship between s and $\dot{s}$ becomes

$$s = \sqrt{\frac{2}{\lambda g}(\dot{s} - \dot{s}_0)}\left[\frac{2\dot{s}_0 + \dot{s}}{3}\right] \tag{17}$$

reducing to equation (3) when $\dot{s}_0 = 0$, and the probability distribution of $\dot{s}$ for the first wheel to come into contact with the deck is given by

$$\varphi_1(\dot{s},\dot{s}_o)$$

$$= \frac{K}{2\sigma_s\sqrt{\pi g\lambda}}\frac{\dot{s}}{\sqrt{\dot{s}-\dot{s}_o}}\exp\left\{-\frac{1}{2\sigma_s^2}\left[\frac{2}{9\lambda g}(2\dot{s}_o+\dot{s})^2(\dot{s}-\dot{s}_o)-\frac{2\mu_s}{3}\sqrt{\frac{2}{\lambda g}}\sqrt{\dot{s}-\dot{s}_o}\,(2\dot{s}_o+\dot{s})+\mu_s^2\right]\right\}. \quad \dots (18)$$

There is a singularily of equation (18) at the point $\dot{s} = \dot{s}_o$ but this is overcome by considering the mean value of $\varphi_1(\dot{s},\dot{s}_o)$ between $\dot{s} = 2\dot{s}_o$ and $\dot{s} = \dot{s}_o$ i.e.

$$\bar{\varphi} = \frac{K}{\dot{s}_o}\left\{\Phi\left(\frac{\frac{4}{3}\sqrt{\frac{2}{\lambda g}}\,\dot{s}_o^{3/2}-\mu_s}{\sigma_s}\right)+\Phi\left(\frac{\mu_s}{\sigma_s}\right)\right\},\ \frac{4}{3}\sqrt{\frac{2}{\lambda g}}\,\dot{s}_o^{3/2} > \mu_s$$

and

$$\bar{\varphi} = \frac{K}{\dot{s}_o}\left\{\Phi\left(\frac{\mu_s}{\sigma_s}\right)-\Phi\left(\left|\frac{\frac{4}{3}\sqrt{\frac{2}{\lambda g}}\,\dot{s}_o^{3/2}-\mu_s}{\sigma_s}\right|\right)\right\},\ \frac{4}{3}\sqrt{\frac{2}{\lambda g}}\,\dot{s}_o^{3/2} \leqslant \mu_s \qquad (19)$$

where $\Phi(x)$ is defined by equation (6).

For the second wheel to touch, the distribution is given by

$$\varphi_2(\dot{s},\dot{s}_o) = \frac{K}{2\sigma_s\sqrt{\pi g\lambda}}\left(\frac{1+a^2}{2a^2}\right)\frac{\dot{s}}{\sqrt{\left(\frac{1+a^2}{2a^2}\right)\dot{s}-\dot{s}_o}}\exp\left\{-\frac{1}{2\sigma_s^2}(x-\mu)^2\right\} \qquad (20)$$

with

$$x = \sqrt{\frac{2}{\lambda g}}\sqrt{\left(\frac{1+a^2}{2a^2}\right)\dot{s}-\dot{s}_o}\left[\frac{2\dot{s}_o+\left(\frac{1+a^2}{2a^2}\right)\dot{s}}{3}\right]. \qquad (21)$$

The probability that a velocity of q ft/sec is exceeded by the first wheel to touch is given by equations (12) but now

$$t_2 = \frac{\frac{1}{3}\sqrt{\frac{2}{\lambda g}}\left[2\dot{s}_o+q\right]\sqrt{(q-\dot{s}_o)}-\mu_s}{\sigma_s}$$

$$t_1 = -\frac{\mu_s}{\sigma_s} \qquad (22)$$

and for both wheels by equations (14) and (15) where now

$$t_2' = \frac{\frac{1}{3}\sqrt{\frac{2}{\lambda g}}\sqrt{\left(\frac{1+a^2}{2a^2}\right)q - \dot{s}_o\left[2\dot{s}_o + \left(\frac{1+a^2}{2a^2}\right)q\right]} - \mu_s}{\sigma_s} \tag{23}$$

$$t_1' = -\frac{\mu_s}{\sigma_s}$$

and t_2 and t_1 by equation (22) above.

Fig.5 shows the effect of an initial velocity of 0.25 ft/sec in the 3 degree roll case where the theoretical curves are compared with the experimental results. The agreement both for the first wheel to touch as well as that for both wheels is quite good, especially when it is remembered that the true curve with which to compare the experimental results lies mainly between the two curves shown.

In Fig.6 is shown the comparison for the 5 degree roll case. In this case, however, the standard deviation of the hover heights is not that obtained from the experimental data. This was because the value obtained was far too small due mainly, it is thought, to the inability to find the hover height in a large number of the landings, as very often the camera was not switched on sufficiently early to record them. The value of 1.5 was selected and, as can be seen from the figure, the agreement is quite good. The major effect of increasing the difficulty of landing is to make larger the mean hover height and the standard deviation. It can also be concluded that the concept of a hover height having a normal distribution as well as the linear relationship between the first and second contact velocities are both reasonable.

In Fig.7(a) and (b) is shown the probability that a particular velocity will be exceeded for the 3 degree roll case. The greatest discrepancies occur at the higher velocities of contact but the agreement is improved when both wheels are considered. Figs.8(a) and (b) gives the case for 5 degrees of roll.

4 THE THEORY FOR A PITCHING DECK

When the landing platform is situated at the stern of the ship, as in the case of the H.M.S. Undaunted during the trials of Ref.1, even a fairly small pitching motion will cause the platform to move with a maximum velocity of more than 3 ft/sec. As this velocity is larger than most of those which will be experienced in practice, it can be seen that if the pilot fails to follow the pitching motion, a heavy landing becomes very probable. However, as a first approximation, it will be assumed that the pilot manages to follow the pitching perfectly before attempting to land. It will be assumed further that the pitching motion is sinusoidal and the pilot begins to descend when the platform has reached its highest point. Thus from Fig.10, it can be seen that if the angle of pitch is θ defined by

$$\theta = \theta_o \sin \omega t \tag{24}$$

then the rotor lift whilst the helicopter follows the pitching motion is given by

$$L = M(g - \ell\, \theta_o\, \omega^2 \sin \omega t) \quad . \tag{25}$$

The platform reaches its highest point when $t = \frac{\pi}{2\omega}$ so that if the decay of rotor lift is again given by equation (2), the lift after the descent has started is

$$L = Mg[1 - \lambda t] - M\,\ell\, \theta_o\, \omega^2 \quad . \tag{26}$$

The equation of motion corresponding to equation (1) is

$$M\, \ddot{s}_{sp} = Mg - L \tag{27}$$

where $\ddot{s}_{sp}$ is the acceleration with respect to fixed space.

By considering the motion of the helicopter relative to the platform, it can be shown that the relationship between the initial height(s) of the helicopter above the platform and the contact velocity ($\dot{s}$) is obtained by eliminating t from

$$s = \frac{1}{6}\, g\lambda t^3 - \ell\, \theta_o (1 - \tfrac{1}{2}\omega^2\, t^2) + \ell\, \theta_o \cos \omega t \tag{28}$$

and

$$\dot{s} = \tfrac{1}{2}\, g\lambda t^2 + \ell\, \omega^2\, \theta_o t - \ell\, \omega\, \theta_o \sin \omega t \tag{29}$$

giving

$$s = F(\dot{s}) \ . \tag{30}$$

If it is assumed again that the hover heights are normally distributed with mean μ_s and standard deviation σ_s then the probability distribution of the contact velocities is given by

$$\varphi(\dot{s}) = \frac{K}{\sigma_s \sqrt{2\pi}} \exp\left\{-\frac{1}{2\sigma_s^2}\,(s - \mu_s)^2\right\} \frac{dF}{d\dot{s}} \tag{31}$$

where K is defined by equation (5) and s is obtained from equation (30). Thus the probability that a given velocity, say q, will be exceeded is given by

$$\Pr(\dot{s} \geq q) = 1 - \int_0^q \varphi(\dot{s})\, d\dot{s} \quad . \tag{32}$$

Following section 3, equation (32) reduces to

$$\Pr(\dot{s} \geq q) = 1 - K\left\{\Phi\left(|t_1|\right) - \Phi\left(|t_2|\right)\right\} \quad t_2 < 0$$

$$\Pr(\dot{s} \geq q) = 1 - K\left\{\bar{\Phi}\left(t_2\right) + \bar{\Phi}\left(|t_1|\right)\right\} \quad t_2 > 0$$

where

$$t_1 = -\frac{\mu_s}{\sigma_s}$$

and

$$t_2 = \frac{F(q) - \mu_s}{\sigma_s} \quad . \tag{34}$$

The above theory is applicable to a deck with no roll. However the roll effect can be obtained using the method of section 3.

5 DISCUSSION OF THEORY AND TRIALS RESULTS

The comparison between the present theory, the results from the rolling platform experiments and those obtained from landings on both ships and on airfields is shown in Fig.10. Firstly, it can be seen that the effect of decreasing the size of the ship is to increase the probability of exceeding a given contact velocity, presumably due to the effect of increased ship motion. For present purposes the airfield can be regarded as a ship of infinite size.

Secondly, the rolling platform results show that for 3 degrees of roll there is no significant difference between the platform contact velocities and those obtained from landings on the airfield. There is, however, a marked increase in contact velocities when the roll angle is increased to 5 degrees. It must be remembered that, in the case of H.M.S. Undaunted trials the helicopters never touched down when the rolling of the ship was greater than 5 degrees. Thus it can be seen that rolling alone cannot explain the increased contact velocities which are presumed to be due primarily to the pitching and heaving of the ship.

Thirdly, to show the effect of the introduction of ship pitching and to illustrate the above theory, a pitching motion of 2 degrees with period 12 secs was selected. Also, to take into account reasonable rolling during the motion, a mean hover height of 0.9 ft and a standard deviation of 1.1 ft were used and λ was taken to be zero i.e. it was assumed that no decay of rotor lift occurred during the descent. Thus from equation (26) it can be seen that the downward acceleration of the helicopter is caused by the $M \ell \theta_0 \omega^2$ term. This loss of rotor lift arises because, prior to the start of the descent, lift had to be taken from the rotor in order to follow the pitching motion combined with the fact that this motion is no longer followed during the descent phase. If the pilot had wished to continue following the motion, however, he would have had to increase the rotor lift obeying equation (25). Thus the theoretical curve in Fig.10 shows the effect of a typical pitching motion on the probability curve.

LIST OF SYMBOLS

M = mass of helicopter (lb)

g = acceleration due to gravity (ft/sec^2)

L = rotor lift (lb ft/sec^2)

s = height of helicopter above deck (ft)

$\dot{s}$ = velocity of descent (ft/sec)

$\ddot{s}$ = downwards acceleration (ft/sec^2)

λ = given by equation (2)

K = given by equation (5)

μ_s = mean hover height (ft)

σ_s = standard deviations of hover height distribution (ft)

$\dot{s}_i$ = velocity of contact of ith wheel ($i = 1,2$) (ft/sec)

a = given by equation (9)

$\bar{k}$ = radius of gyration of the aircraft in roll (ft)

$\bar{\ell}$ = semi-distance between wheels (ft)

φ_i = probability distribution of velocity of contact of ith wheel ($i = 1,2$)

t_i = defined by equation (13) ($i = 1,2$)

t_i' = defined by equation (16) ($i = 1,2$)

LIST OF SYMBOLS (CONT'D.)

A, A' = defined by equation (15)

$\dot{s}_o$ = initial velocity of descent (ft/sec)

Φ = defined by equation (6)

θ = pitch angle

θ_o = amplitude of pitching oscillation

ω = frequency of pitching oscillation

T = period of pitching oscillation

$\ddot{s}_{sp}$ = acceleration of helicopter with respect to fixed space

ℓ = distance of landing platform from the centre of the pitching oscillation

$F(\dot{s})$ = defined by equation (30)

LIST OF REFERENCES

No.	Author	Title, etc.
1		Unpublished M.O.A. Report.
2		This facility simulates the rolling motion of typical ships in the 3-6000 ton range. The motion of the platform is the same as that of a deck 22 ft above the roll axis of a ship: roll period is 8 seconds and roll amplitudes are adjustable up to a maximum of ±15°

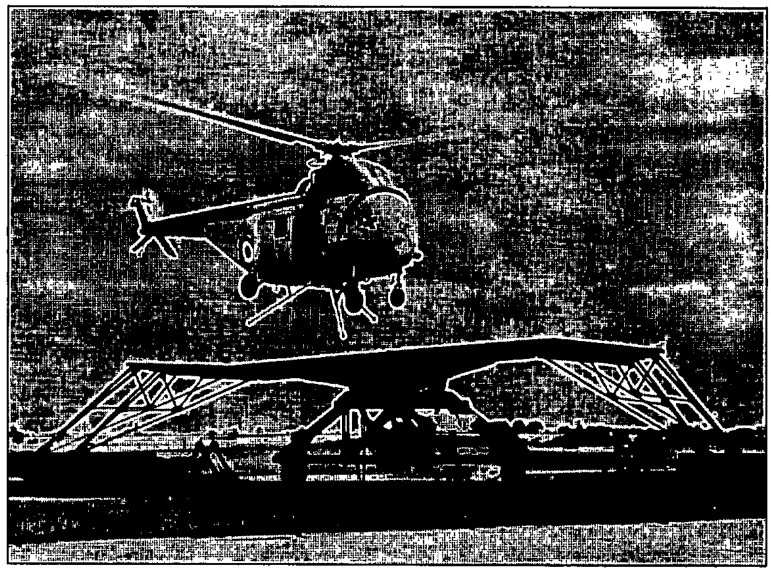


FIG.1. HELICOPTER LANDING ON ROLLING PLATFORM

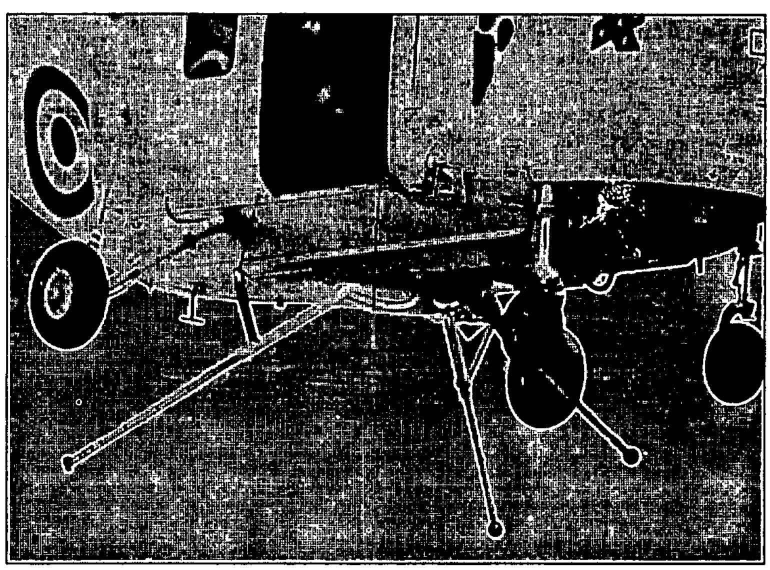


FIG.2. APPARATUS FOR THE MEASUREMENT OF THE TOUCHDOWN VELOCITIES

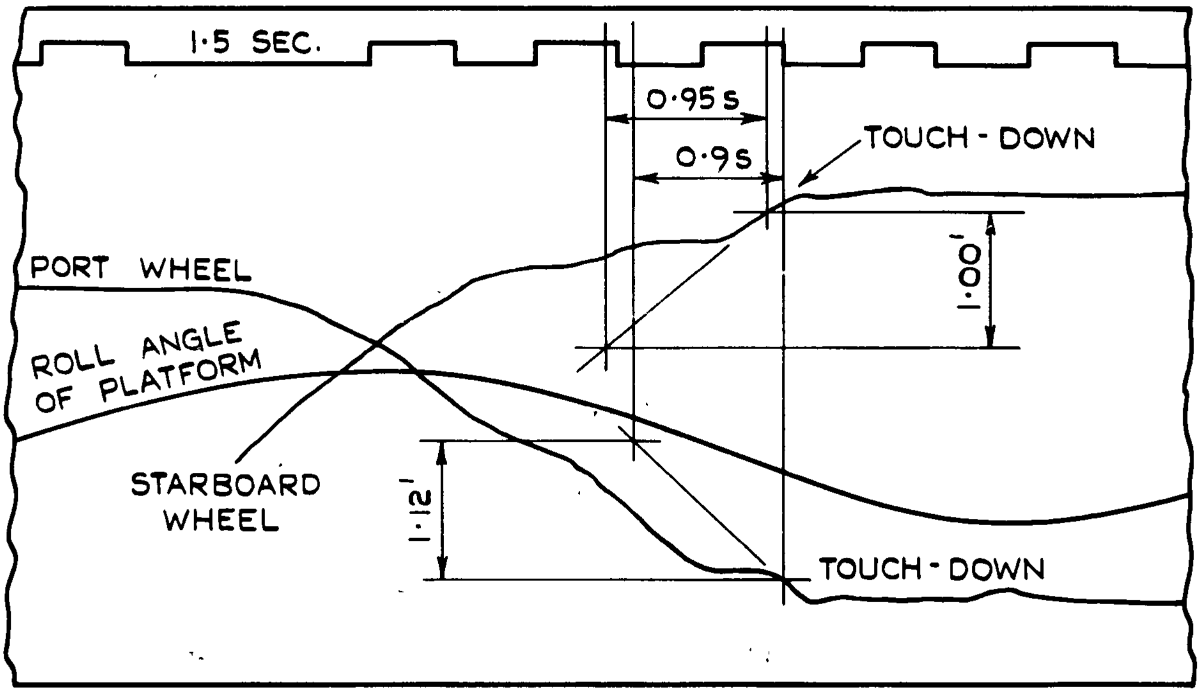


FIG.3. TYPICAL RECORD

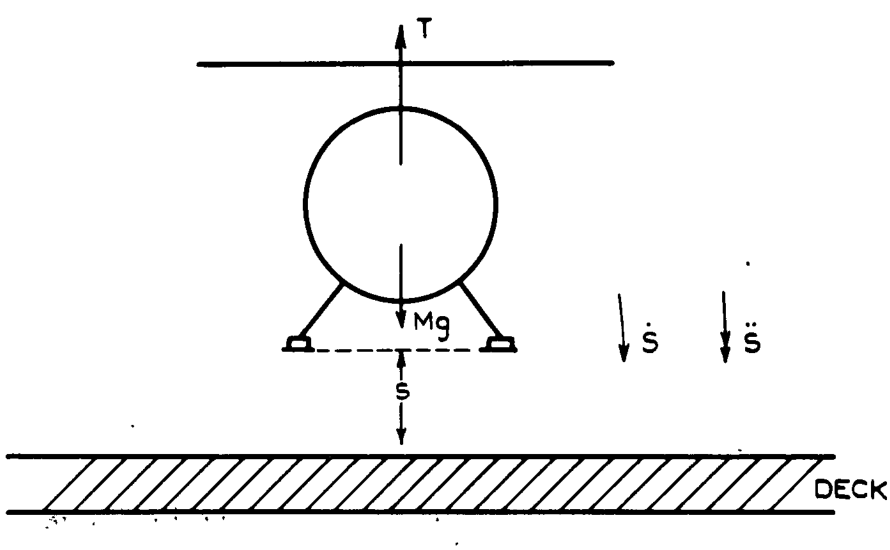


FIG.4. KEY TO ANALYSIS

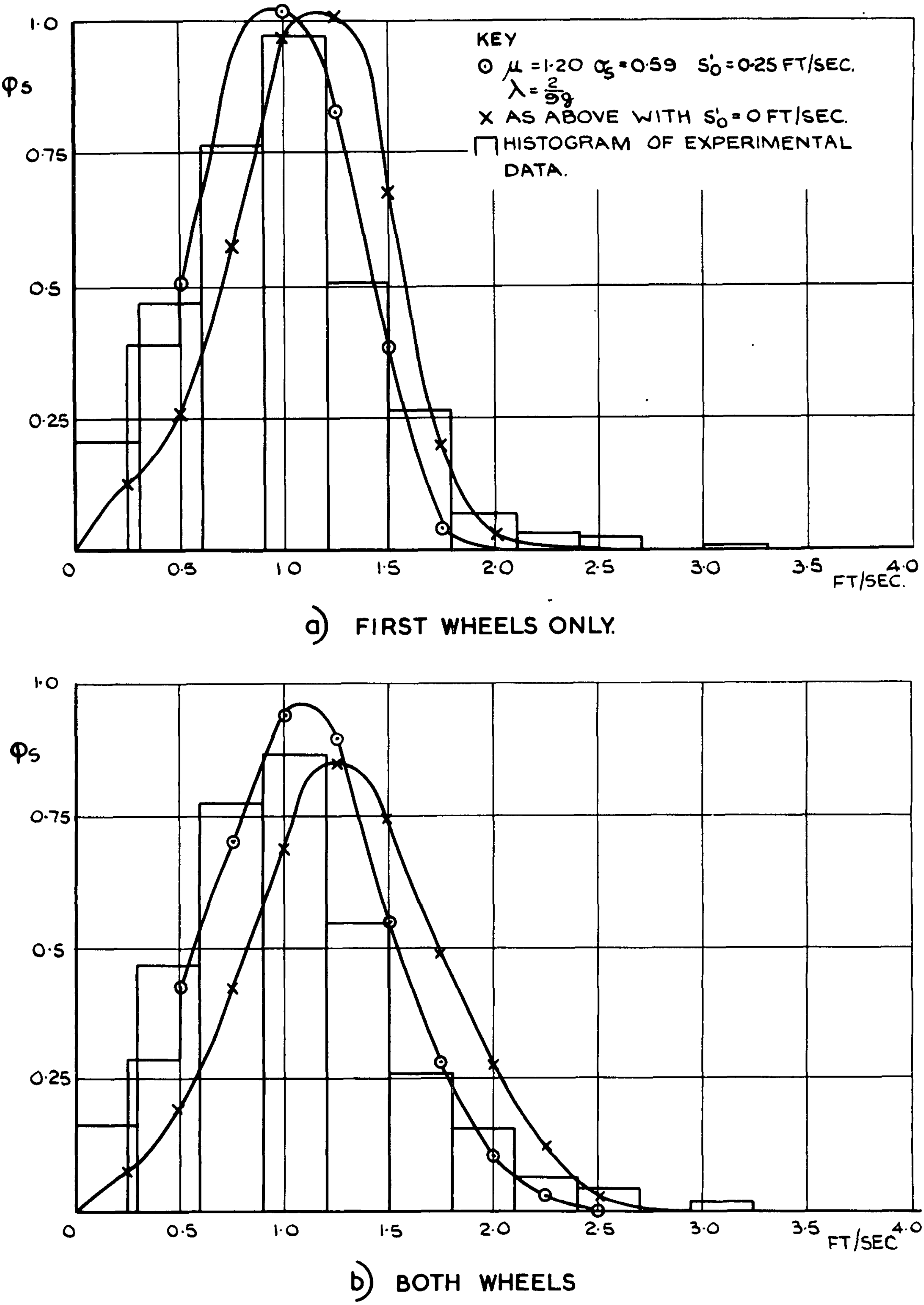
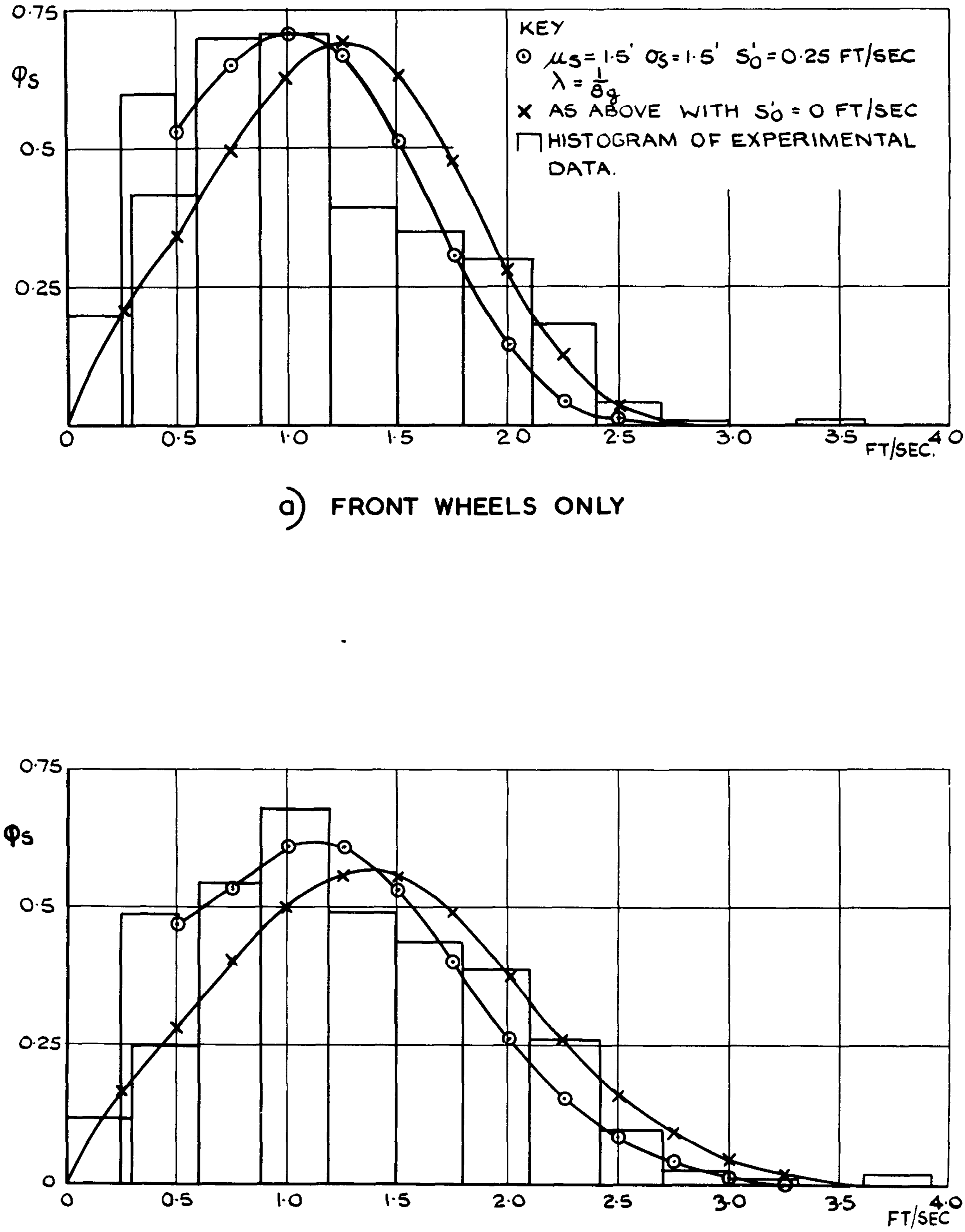


FIG. 5. PROBABILITY DISTRIBUTIONS OF LANDING VELOCITIES – 3° ROLL



a) FRONT WHEELS ONLY

b) BOTH WHEELS

FIG.6. PROBABILITY DISTRIBUTIONS OF LANDING VELOCITIES – 5° ROLL

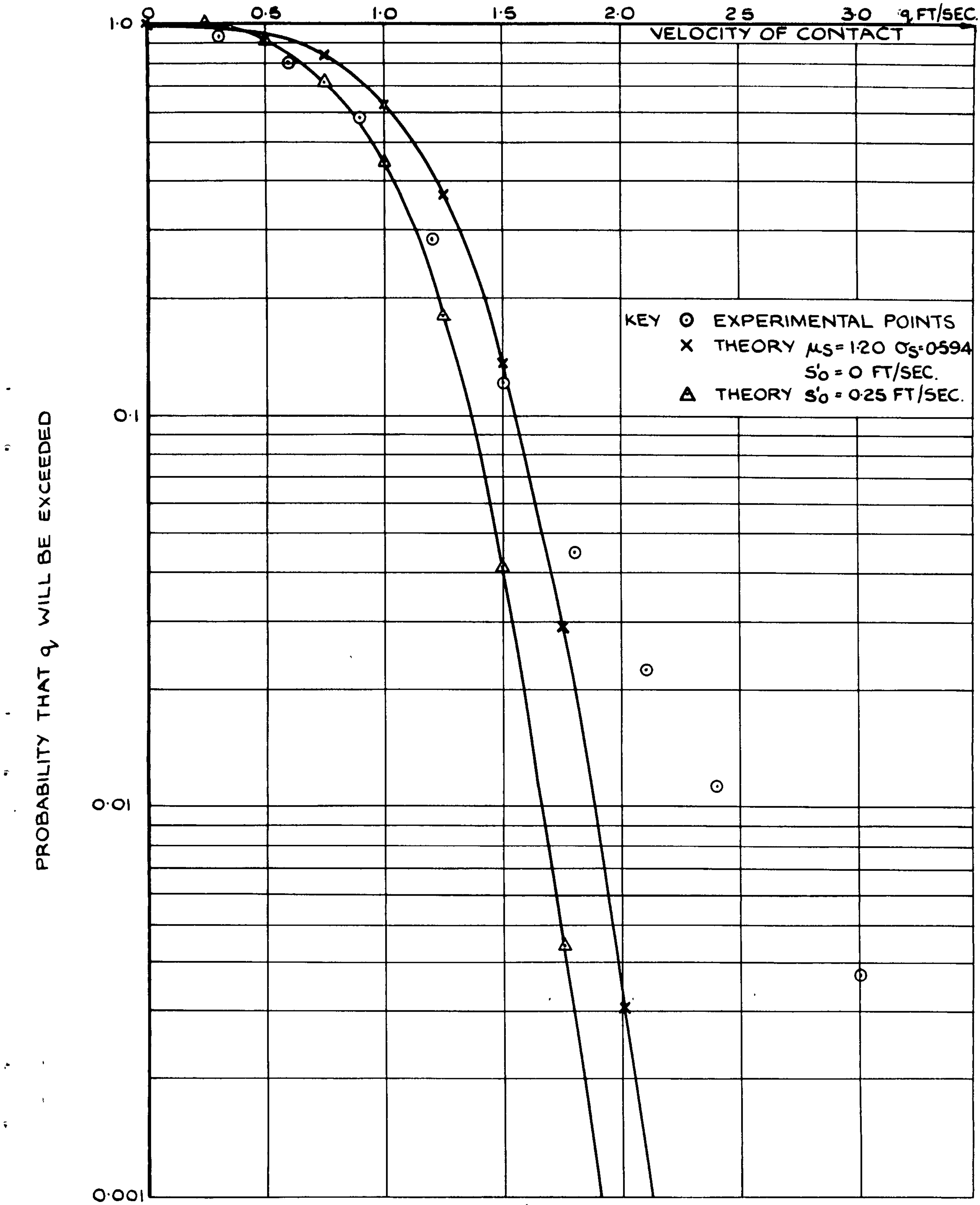


FIG. 7a. PROBABILITY THAT A CERTAIN VELOCITY WILL BE EXCEEDED.
(3° ROLL – FIRST WHEEL ONLY.)

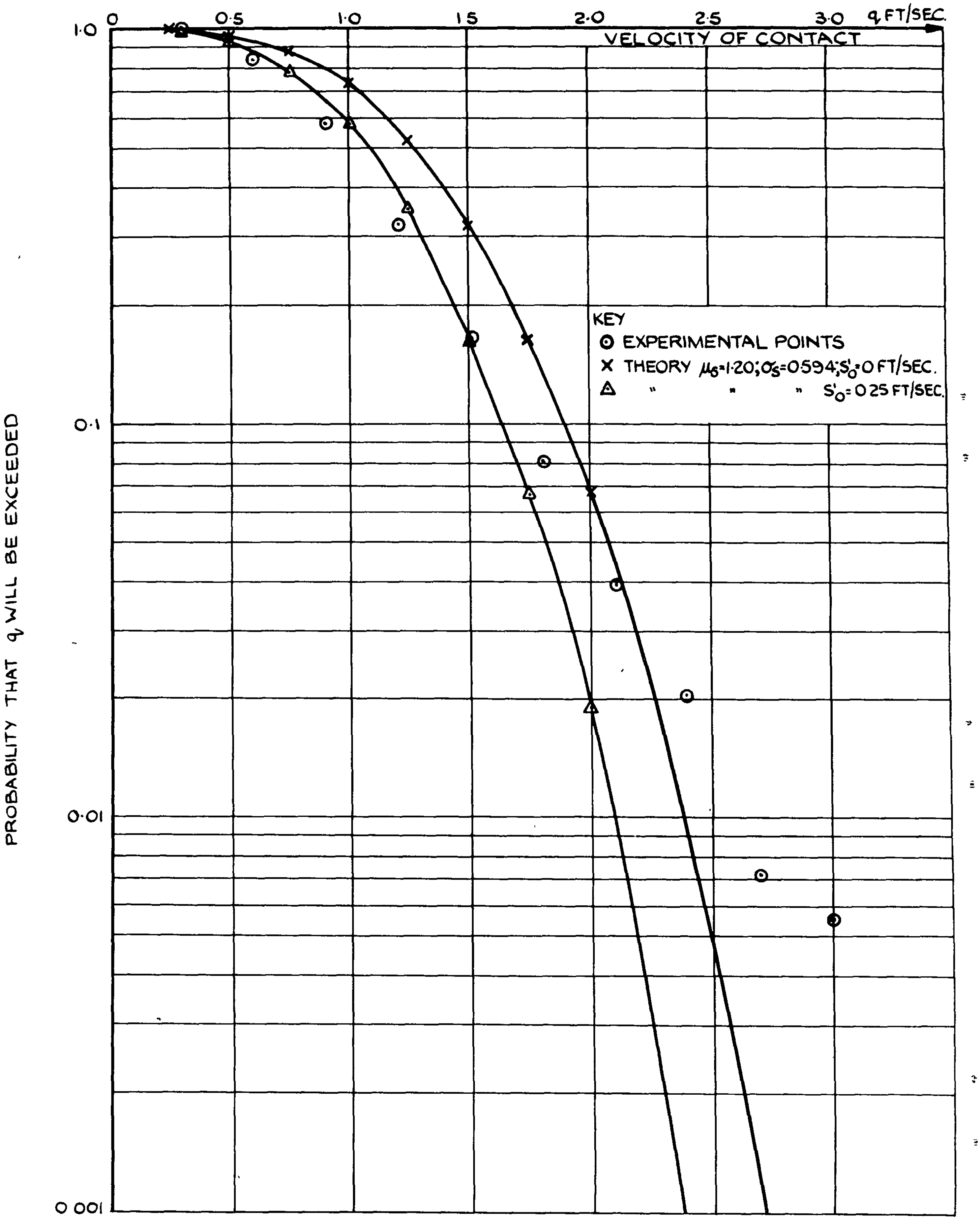


FIG.7 b. PROBABILITY THAT A CERTAIN VELOCITY WILL BE EXCEEDED

(3° ROLL – BOTH WHEELS.)

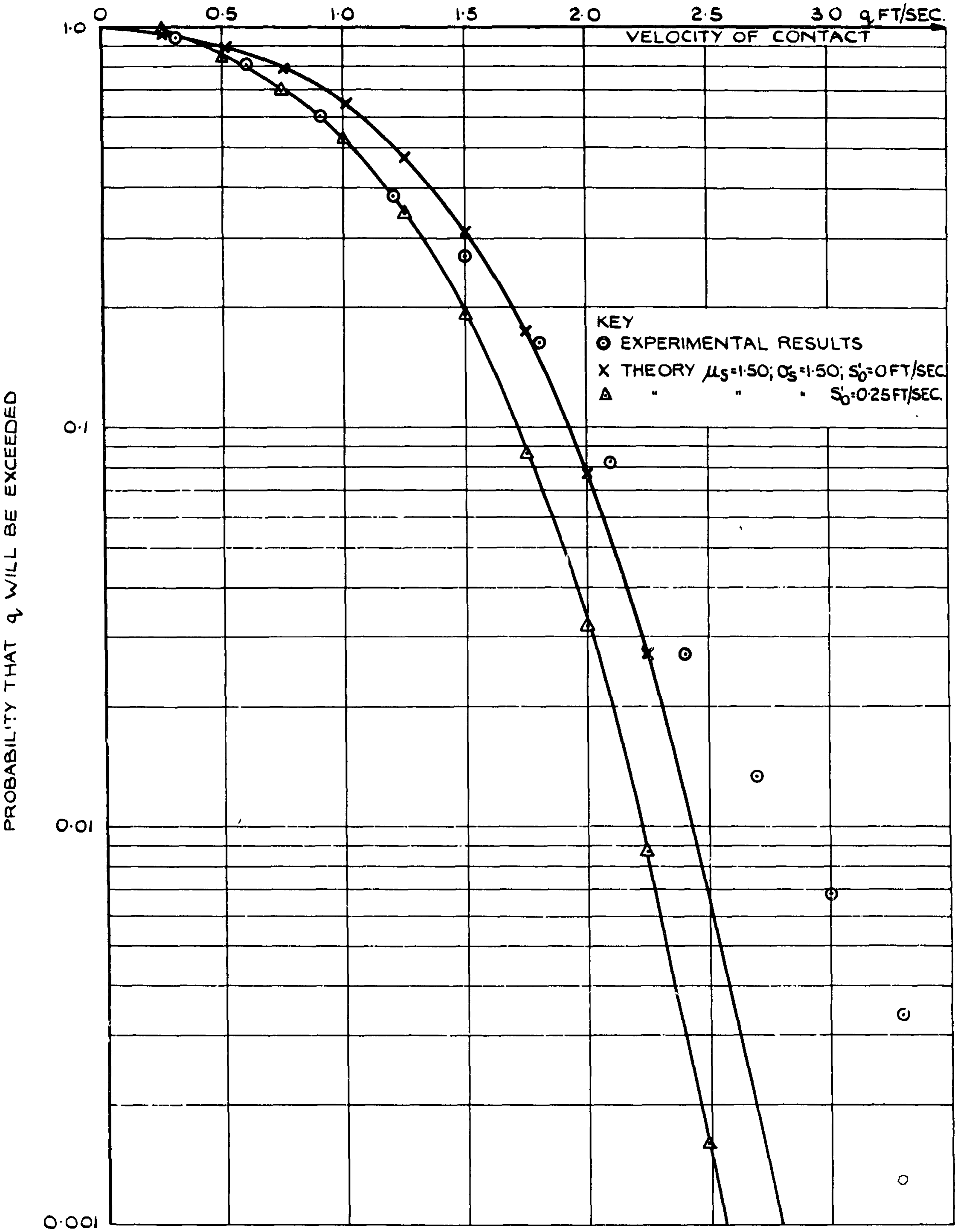


FIG. 8a. PROBABILITY THAT A CERTAIN VELOCITY WILL BE EXCEEDED.
(5° ROLL - FIRST WHEEL ONLY)

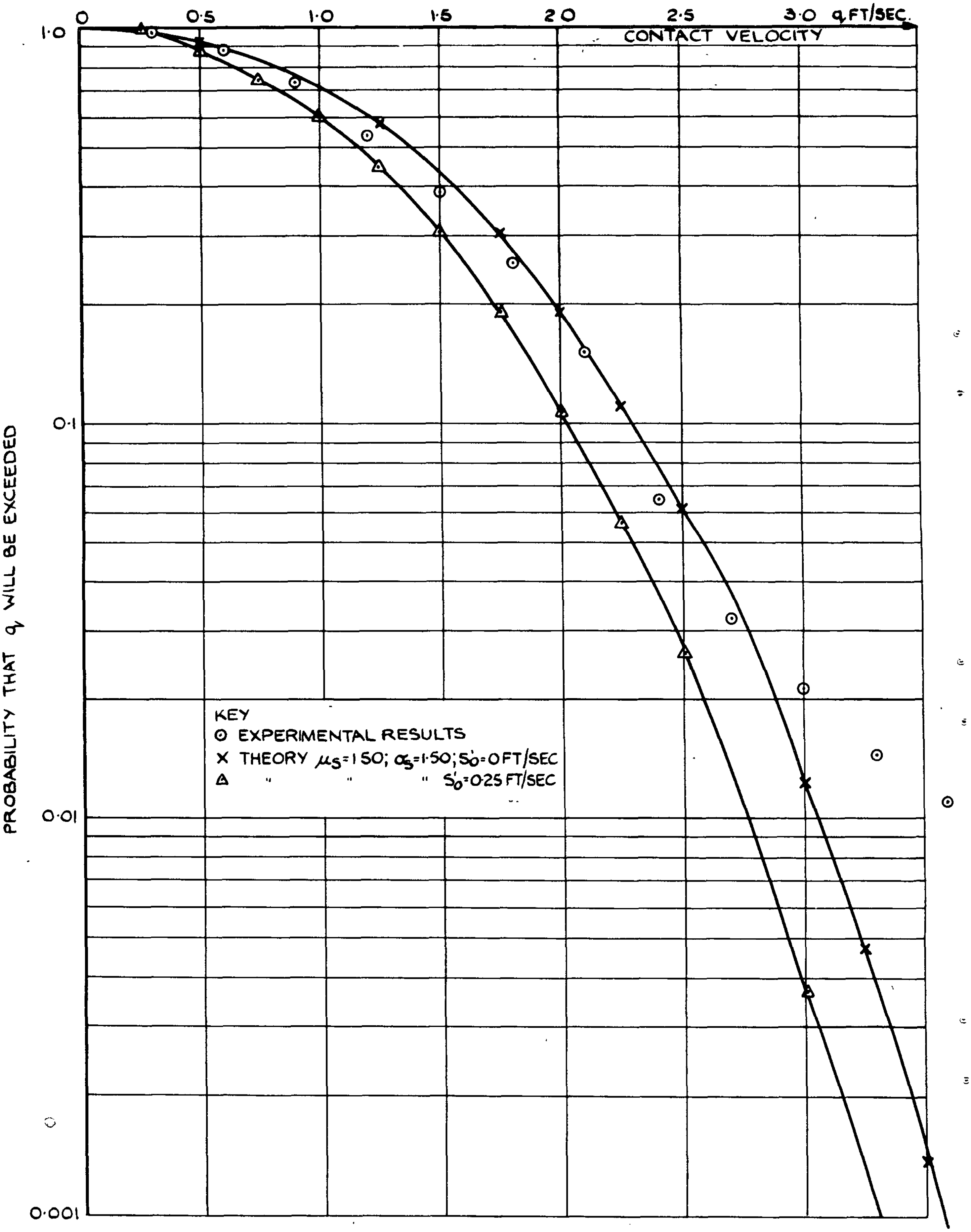


FIG. 8 b. PROBABILITY THAT A CERTAIN VELOCITY WILL BE EXCEEDED
(5° ROLL – BOTH WHEELS)

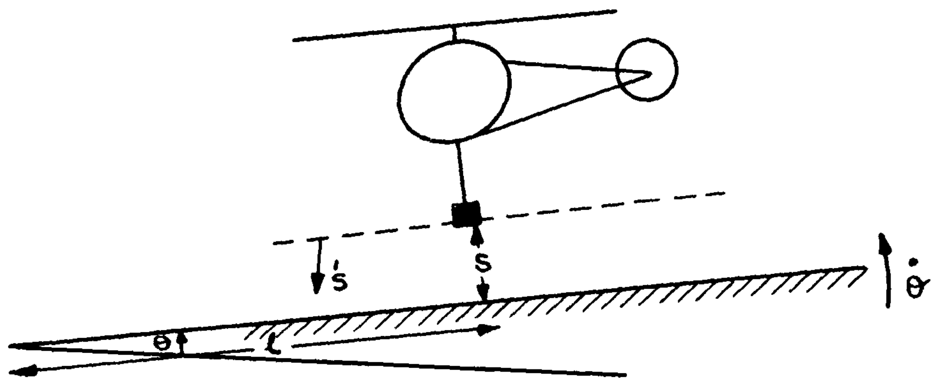


FIG. 9. KEY TO PITCH ANALYSIS.

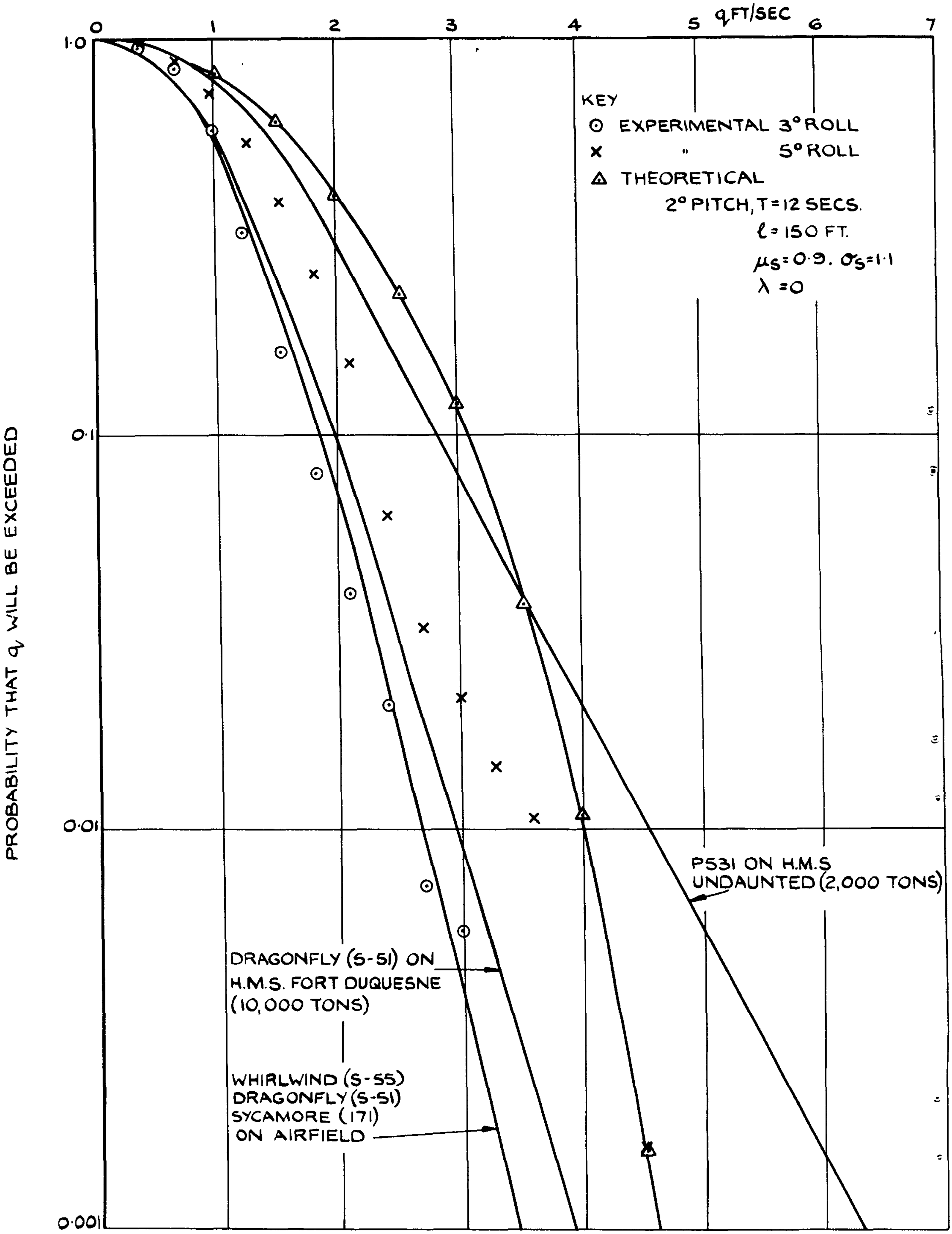


FIG. 10. COMPARISON OF THE PROBABILITIES THAT A GIVEN CONTACT VELOCITY WILL BE EXCEEDED.

(PITCHING & ROLLING)

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