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The Performance of Fans in Hovercraft – A method of Reducing Experimental Results

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Summary.

A method for reducing data on hovercraft fan performance is proposed which is expected to lead to a simplification of model and flight test procedures.

The method is shown to be theoretically justified, and supporting experimental evidence is provided from models with both solid and flexible duct geometry.

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*Replaces R.A.E. Techn. Report No. 65 240 – A.R.C. 28 225.

1. *Introduction.*

A programme of research to investigate the performance of fans in a model hovercraft has been in progress over the past three years at the Naval Air Department. The fans have been tested at different r.p.m. and with different model weights, the fan power, volume flow, and model hoverheight being recorded for each condition. It has been customary to present the data as a family of curves showing the variation of fan performance with hoverheight at each model weight.

Although this method of presenting the results is satisfactory, some means was sought of eliminating the dependence of the curves on model weight. A consideration of the theoretical equations for the jet performance together with the argument from continuity that the volume flow through the fan must equal that through the jets supported the view that the volume flow results could be reduced in the desired manner. A further consideration of the particular environment presented to the fan by the hovercraft suggested that theoretical justification also existed for a similar treatment of the r.p.m. and power data. These arguments are described in this Report.

Experimental evidence from models with both solid and flexible geometry has been examined to test the conclusions of the argument and the method of reduction, and the practical implications of the method have been briefly discussed.

2. *The Proposition.*

2.1. *Consideration of Edge Jet Performance.*

One of the assumptions which has been common to many of the theories describing the performance of the edge jet of a hovercraft is that of constant total head across and along the jet. It follows from this assumption that in the equations defining cushion pressure, volume flow, and jet lift, a dependence on the value of jet total head is introduced. This is seen, for example, in the theory due to Elsley[1] for a deflected jet, where we have

$$p_c = H_j(1-e^{-2x}) \tag{1}$$

$$Q = \sqrt{H_j}\sqrt{\frac{2}{\rho}}\frac{h\,l}{1+\cos\theta}(1-e^{-x}) \tag{2}$$

$$L_j = H_j\frac{h\,l\sin\theta}{1+\cos\theta}(1-e^{-2x}) \tag{3}$$

where $x = \frac{t}{h}(1+\cos\theta)$, a dimensionless edge jet parameter. In three-dimensional models or full size craft, the distribution of flow to the edge jet is usually such that variations in total head exist, and it is often impracticable to measure total-head values satisfactorily under test conditions. For the presentation of experimental results in non-dimensional form, therefore, it is desirable that the performance equations should be re-expressed such that the dependence on jet total head is eliminated. Provided that the weight of the model or craft is known, and under equilibrium conditions, the weight may be approximately equated to the combined cushion and jet lifts by the relationship:

$$\text{weight} = \text{cushion lift} + \text{jet lift}.$$

Using the symbol S to denote the cushion area bounded by the edge jet, we have

$$W = p_c\,S + L_j$$

which, using equations (1) and (3), leads to

$$\frac{H_j}{W} = \left[(1-e^{-2x}) \left\{ S + \frac{h\,l \sin\theta}{1+\cos\theta} \right\} \right]^{-1}. \tag{4}$$

The use of equation (4) with equations (1) to (3) therefore enables the jet performance equations to be expressed as functions of craft weight.

Of particular interest for our purpose is the expression for volume flow, which becomes

$$Q = \sqrt{W} \sqrt{\frac{2}{\rho}} \frac{h\,l}{1+\cos\theta} \left\{ S + \frac{h\,l \sin\theta}{1+\cos\theta} \right\}^{-\frac{1}{2}} \frac{(1-e^{-x})}{(1-e^{-2x})^{\frac{1}{2}}}. \tag{5}$$

When dealing with experimental results gained from a particular craft for which S, θ, t and l are constant, a convenient form for the presentation of results is that of

$$\frac{Q\sqrt{\sigma}}{\sqrt{W}} \text{ as a function of } h$$

where σ is the relative density. Depending on the extent to which the theory adequately describes the behaviour of the real jet, experimental volume-flow results reduced in this way might be expected to lie on a common curve.

2.2. *Consideration of the Fan-duct Combination.*

The behaviour of a fan of given design is best described in coefficient form. As an example, the coefficients of volume flow and pressure rise respectively are defined such that

$$\phi \propto \frac{Q}{N}$$

$$\psi \propto \frac{p}{N^2}$$

where Q is the volume flow, p the pressure rise, and N the fan r.p.m. A coefficient of power input to the fan is also defined,

$$K_p \propto \frac{HP}{N^3} \frac{1}{\sigma}.$$

The relationships which exist between ϕ, ψ, and K_p for a given fan are frequently referred to as the fan characteristics. An example of these is shown in Fig. 1.

We now postulate the condition that a fan is operating at a given point on its characteristic. ϕ and ψ are therefore constant, and we may write

$$Q \propto N$$

$$p \propto N^2.$$

The r.p.m. N can be eliminated between these two expressions in order to relate p with Q, and we have

$$p \propto Q^2.$$

The conditions required to pump air through a duct are now considered. A duct of given geometry and construction offers resistance to the passage of air through it, and, providing the Reynolds Number of the flow is sufficiently high, the pressure required to overcome the resistance is proportional to the square of the volume flow. It will be noted that this is the same relationship as that obtained for the particular operation of the fan just described, and we thus see that the condition of constant fan pressure rise and flow coefficients is compatible with that of given duct resistance. Expressed in another way, we conclude that if a fan is supplying air to a duct of given resistance, the performance of the fan at all rotational speeds is defined by the particular working point on the fan characteristic appropriate to that resistance.

The case of a fan in an edge jet hovercraft may now be considered. The duct shape and geometry are assumed to remain constant. For constant craft weight, it is clear that the only change in downstream resistance (as presented to the fan) is that which arises from change of hoverheight. It follows from the consideration of fan-duct compatibility that a unique relationship exists between hoverheight and the working point on the fan characteristic. Moreover, changes in craft weight at constant hoverheight will not affect the working point, as the required change of pressure with weight is accommodated by a change of fan r.p.m. The conclusion is therefore reached that for a given fan-hovercraft combination, the coefficients of volume flow, pressure rise, and power will have unique relationships with hoverheight, independent of craft weight.

It has been shown in Section 2.1 that for a particular craft it is theoretically satisfactory to express volume flow data in the reduced form of $Q\sqrt{\sigma}/\sqrt{W}$ with hoverheight. But if it is true that the flow coefficient ϕ varies uniquely with hoverheight for a similar environment, then, because $\phi \propto Q/N$, it follows that the fan r.p.m. data can justifiably be expressed in the reduced form

$$\frac{N\sqrt{\sigma}}{\sqrt{W}} \text{ with } h.$$

Further, with $K_p \propto HP/N^3\sigma$, it is readily shown that the reduced form for the fan power data is

$$\frac{HP\sqrt{\sigma}}{W\sqrt{W}} \text{ with } h.$$

3. *Supporting Evidence.*

Tests have been made on a $\frac{1}{3}$ scale half-model of a Britten-Norman CC2 hovercraft, and volume flow, fan r.p.m. and fan power were measured at different weights and hoverheights. The radial flow fan installed in the model was of the type E1 designed by the Department for high static efficiency[2]. The fan was driven through a belt drive by an electric motor. The power produced by the motor was directly measured, and the correction for belt loss obtained from calibration. The model was fixed relative to the rig, and exerted lift thrust on a counterbalanced moving groundboard. Weights could be added to suspension weight pans in order to achieve change of effective model weight. A photograph of the rig is shown in Fig. 2. The intake for measurement of volume flow will be seen above the model hull.

3.1. *Rigid Geometry Model.*

The first series of results was obtained from a rigid geometry model with edge jets inwardly inclined at 30 deg to the horizontal. This was representative of the original configuration of the full-scale craft. The longitudinal stability jets were in use for the tests but this would not be expected to alter the principles of the data reduction. The model weight variation was

$$83 \leqslant W \leqslant 148 \text{ lb.}$$

Fig. 3 shows the volume-flow data in the reduced form $Q\sqrt{\sigma}/\sqrt{W}$ with hoverheight for five model weights. The scatter of the points is very small, and it is not possible to associate any consistent shift of the points with craft weight. The theoretical justification for presenting the results in this form is thus supported.

Fig. 4 and 5 show the variation of fan and power coefficients with hoverheight. These curves support the theoretical conclusion that the variation of the fan coefficients with hoverheight is independent of craft weight. The scatter of Fig. 5 is not untypical of power-coefficient results, and is thought to be partly due to the dependence of this coefficient on the third power of fan r.p.m.

Fig. 6 and 7 show the fan r.p.m. and power in the reduced forms of $N\sqrt{\sigma}/\sqrt{W}$ and $HP\sqrt{\sigma}/W\sqrt{W}$, respectively, with hoverheight. The scatter of the points is considered to be within the experimental limits for these tests. The satisfactory way in which the data reduces confirms that the basis of the argument presented in the earlier section is sound.

3.2. *Flexible Model.*

The justification given in Section 2.1 for presenting volume-flow data in a reduced rather than non-dimensional form only exists where S, θ, t and l are constant. This is also a necessary condition for the argument deriving the reduced forms of fan r.p.m. and power. On hovercraft which make use of flexible structure for part or all of the edge jet ducting, there clearly exists the possibility that these geometric quantities will change in value with varying craft weight. If the results are presented in the reduced form and a dependence on craft weight is observed, it must be concluded that such dependence is due to the changing geometry of the flexible ducts.

The second series of results to be described was obtained from a flexible model with edge jets inclined at an average 52 deg to the horizontal. The flexible duct was one of a series developed in conjunction with R. & D.E., Cardington, and was of a fairly rigid type. The longitudinal stability jets were in use for the experiment, and model weights of 83 lb and 111 lb were tested. Due to the slightly uneven lower edge of the inflated structure, it was difficult to define the zero hoverheight datum, and hoverheight measurement between tests was probably only accurate to 1/10 inch. It will be noted that such an error would appear as a consistent shift over the whole range of hoverheight. A flexible model similar to that tested is shown in Fig. 8.

Fig. 9 shows the volume flow data in the reduced form plotted against hoverheight. Separate curves have been drawn through the points for the two model weights, although it should be noted that the difference between them is only slightly greater than the possible error in hoverheight measurement. The fan r.p.m. data, Fig. 10, is such that only a single line can be drawn for both weights, whilst the fan power data, Fig. 11, again shows a small dependence on model weight. The flow and power coefficients are shown in Figs. 12 and 13.

It can be concluded that this particular model does not show a very large change of geometry with craft weight, and further tests with various types of flexible skirt would clearly be desirable.

4. *Practical Implications.*

Although additional experimental evidence from highly flexible models would be necessary in order to determine the maximum likely effect of structure deformation on fan behaviour, the presentation of fan performance data in the suggested form for craft with solid geometry is supported by the available evidence. However, for both types of hovercraft, a simplification of model or flight test procedure may be adopted.

For a craft of rigid geometry, it is clearly only necessary to carry out tests at the lightest weight in order to achieve the greatest range of hoverheight. The variation of fan volume flow, r.p.m. and power at any other required weight may than be readily determined from the reduced performance data. For craft with flexible structures, it will also be necessary to test at some greater weight so that the effect of structure deformation may be assessed.

For a particular fan it is possible to define static and total efficiencies based on the pressure rise, volume flow, and power input. These are shown for a typical radial flow fan in Fig. 1, the efficiencies being defined in the List of Symbols. The use of these defined efficiency functions together with fan input and edge jet powers in their reduced forms would yield by difference a 'duct-loss' term which would be uniquely related to hoverheight for a given hovercraft. Whilst the value of such a term might be somewhat limited by nature of its definition, it is thought that it might introduce a means of comparing the efficiencies of ducts of differing design.

5. *Conclusions.*

The conclusions of the Report are briefly summarised.

For hovercraft of constant geometry.

(i) The presentation of volume flow data in the form $\frac{Q\sqrt{\sigma}}{\sqrt{W}}$ yields a relationship which is uniquely related to hoverheight over a range of craft weight.

(ii) For a given fan-hovercraft combination, if the fan performance is expressed in coefficient form, the coefficients are uniquely related to hoverheight over a range of craft weight.

(iii) For practical purposes, it is suggested that fan r.p.m. and power are best expressed in the form $\frac{N\sqrt{\sigma}}{\sqrt{W}}$ and $\frac{HP\sqrt{\sigma}}{W\sqrt{W}}$ respectively. This presentation yields relationships which are uniquely related to hoverheight over a range of craft weight.

For hovercraft of flexible geometry.

(iv) The extent to which conclusions (i) to (iii) are borne out in practice is a measure of the extent to which flexible ducts deform under the differing inflation pressures which arise from changing craft weight.

LIST OF SYMBOLS

b	Depth of fan exit, ft
e	Fan depth to radius ratio $= b/R$
h	Hoverheight, ft unless otherwise indicated
H_j	Jet total head, relative to ambient pressure, lb/ft^2
HP	Input power to fan
K_p	Fan power coefficient $= HP/\Omega^3\, e\, R^5\, \rho$
l	Edge jet peripheral length (mean), ft
l_s	Stability jet length, ft
L_j	Edge jet lift, lb
N	Fan r.p.m.
p_c	Cushion pressure, relative to ambient, lb/ft^2
p	Fan pressure rise (general) lb/ft^2
p_s	Mean static-pressure rise across fan, lb/ft^2
p_t	Mean total-pressure rise across fan, lb/ft^2
Q	Volume flow, ft^3/sec
R	Fan outer radius, ft
S	Cushion area, bounded by edge jet, ft^2
t	Edge jet thickness, ft unless otherwise indicated
t_s	Stability jet thickness, ft unless otherwise indicated
W	Model or craft weight, lb
η_s	Fan static efficiency $= Q\, p_s/550 \times HP$
η_t	Fan total efficiency $= Qp_t/550 \times HP$
θ	Edge jet angle, deg
ρ	Air density, slug/ft^3
σ	Relative air density

ϕ	Fan flow coefficient $= Q/2\pi\,\Omega\, e\, R^3$
ψ_s	Fan static-pressure rise coefficient $= p_s/\Omega^2\, R^2\, \rho$
ψ_t	Fan total-pressure rise coefficient $= p_t/\Omega^2\, R^2\, \rho$
Ω	Fan rotational speed, rad/sec $= N \times 2\pi/60$

REFERENCES

No.	*Author*	*Title, etc.*
1	G. Elsley	Two-dimensional hovercraft lift. Saunders-Roe Ltd., East Cowes. Unpublished 1959. [Theory available in Stanton-Jones, 'Some Design Problems of Hovercraft' ARC.23 752, IAS Paper 61–45, Jan. 1961].
2	P. Brotherhood	Development of improved fans for the Britten-Norman CC2–001 cushioncraft. R.A.E. Technical Report No. 66 271, August 1966.

Table of Model Dimensions

Item	Solid geometry	Flexible
l (ft)	12·00	12·67
l_s (ft)	7·80	7·00
S^+ (ft^2)	18·06	21·13
t (in.)	1·33	1·90*
t_s (in.)	1·33	1·50*
θ (deg)	30	52*

$^+$includes area of stability jets, excludes edge jets

*average

Fan Type E1

Characteristics of operation are shown in Fig. 1.

$$b = 0{\cdot}704 \text{ ft}$$

$$R = 1{\cdot}160 \text{ ft}$$

$$e = 0{\cdot}607$$

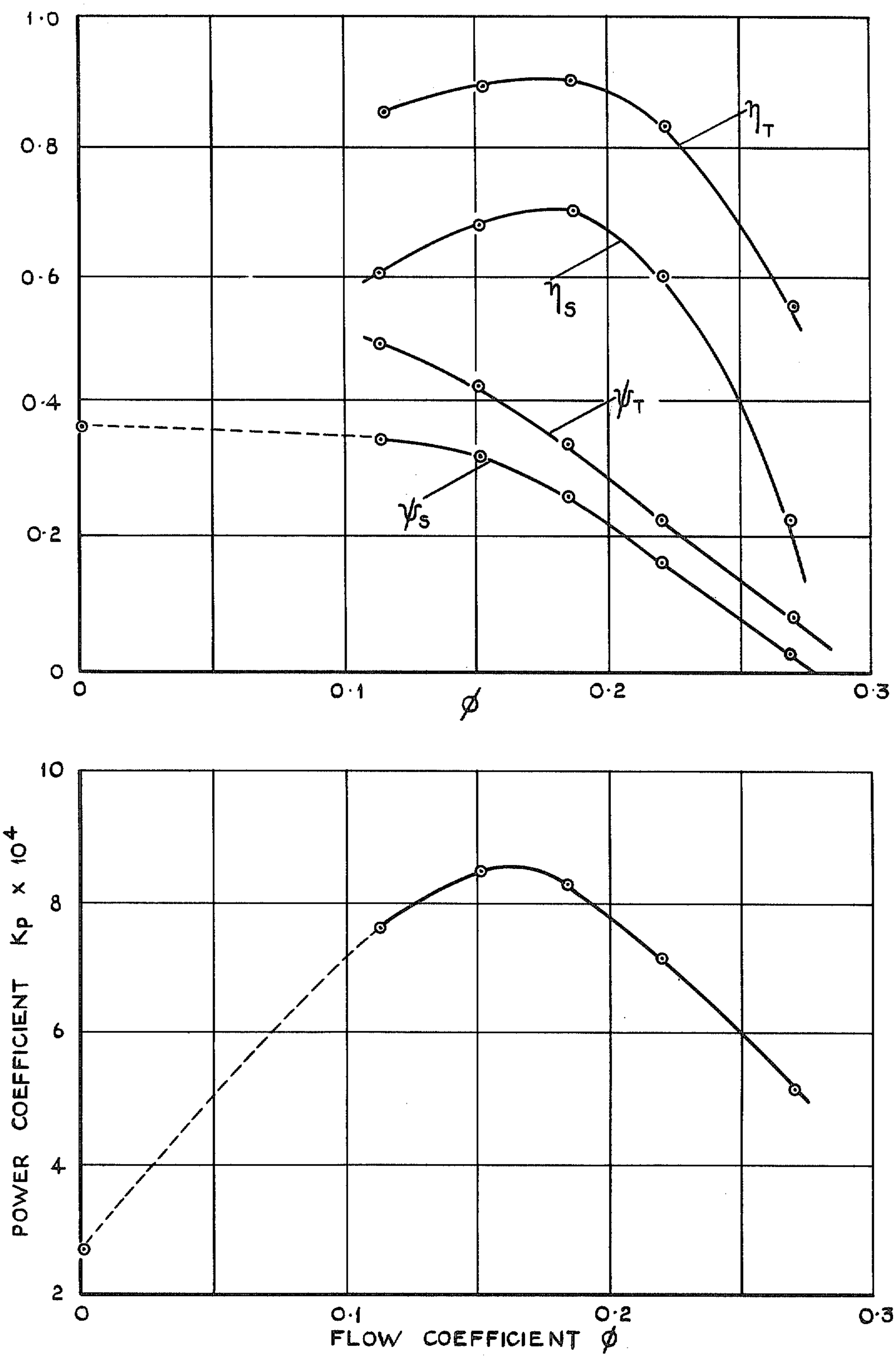


FIG. 1. Fan type E1 characteristic curves.

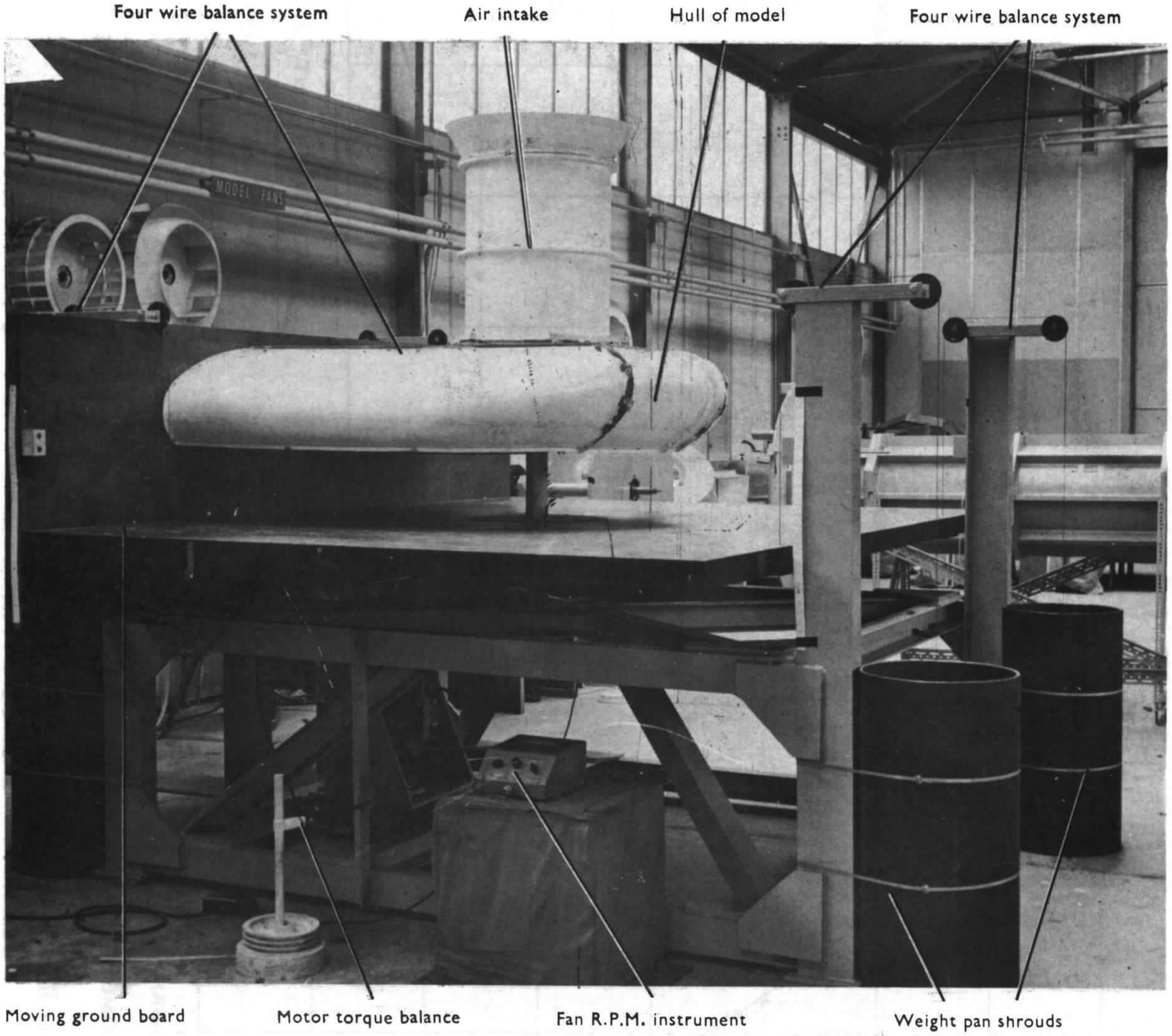
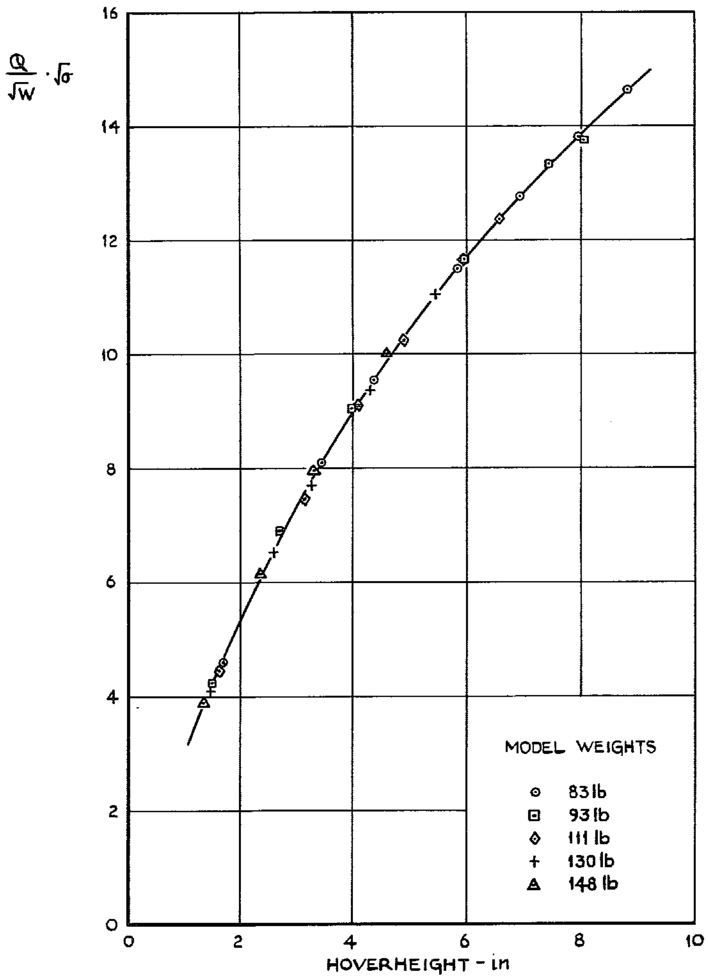
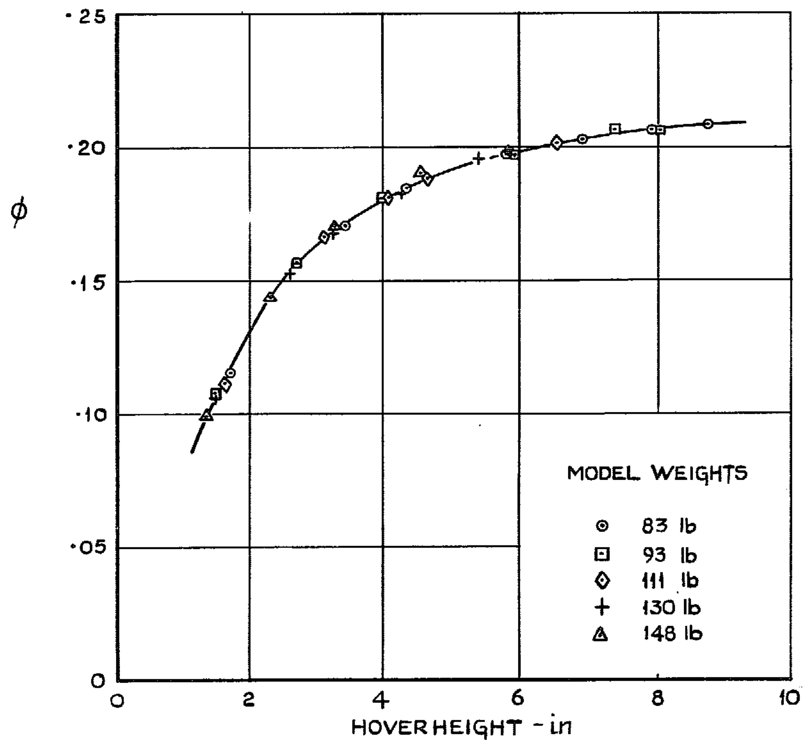


FIG. 2. The solid geometry model on the test rig.



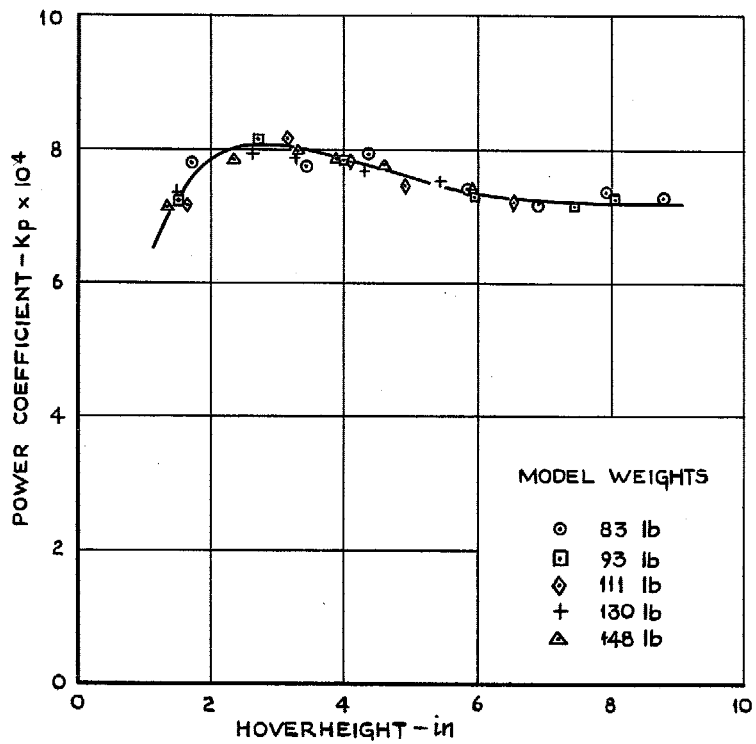
SOLID GEOMETRY MODEL

FIG. 3. Change of volume flow with hoverheight.



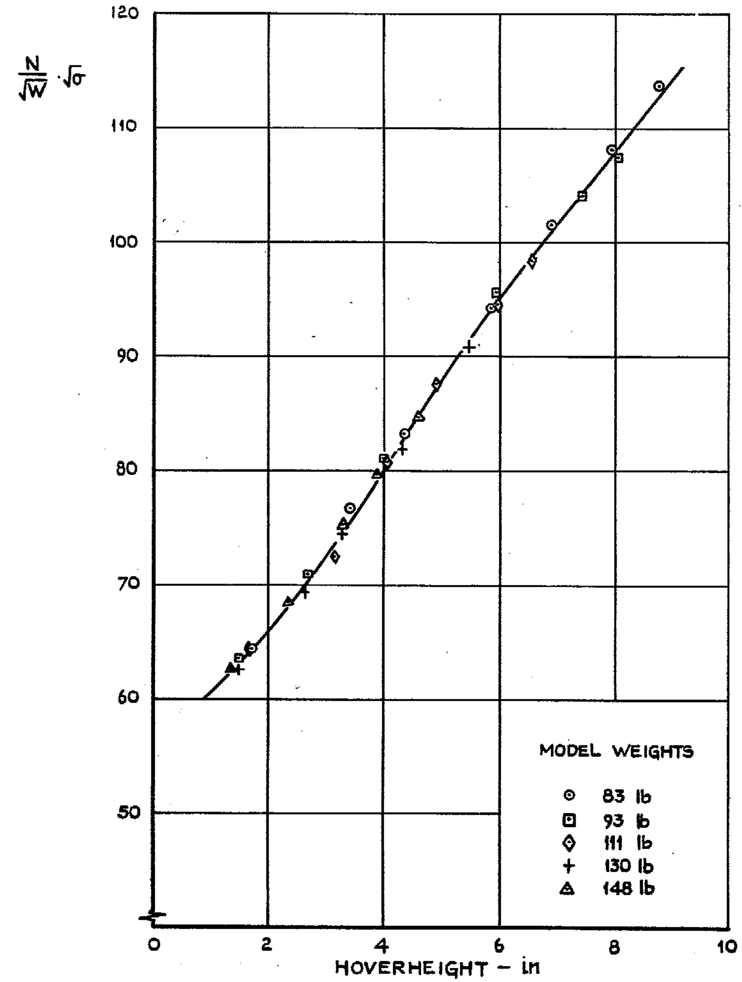
SOLID GEOMETRY MODEL

FIG. 4. Change of ϕ with hoverheight.



SOLID GEOMETRY MODEL

FIG. 5. Change of K_p with hoverheight.



SOLID GEOMETRY MODEL

FIG. 6. Change of r.p.m. with hoverheight.

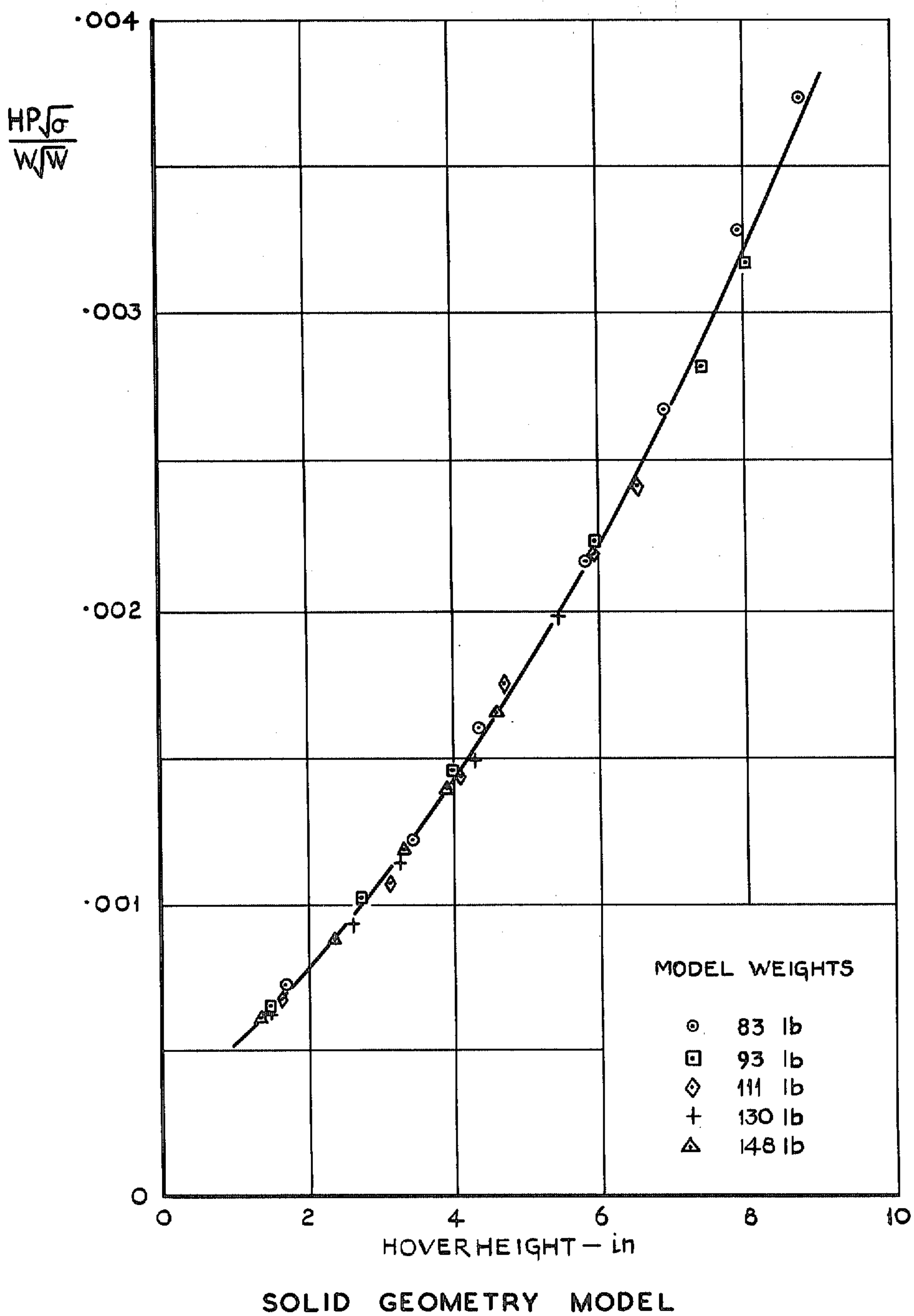
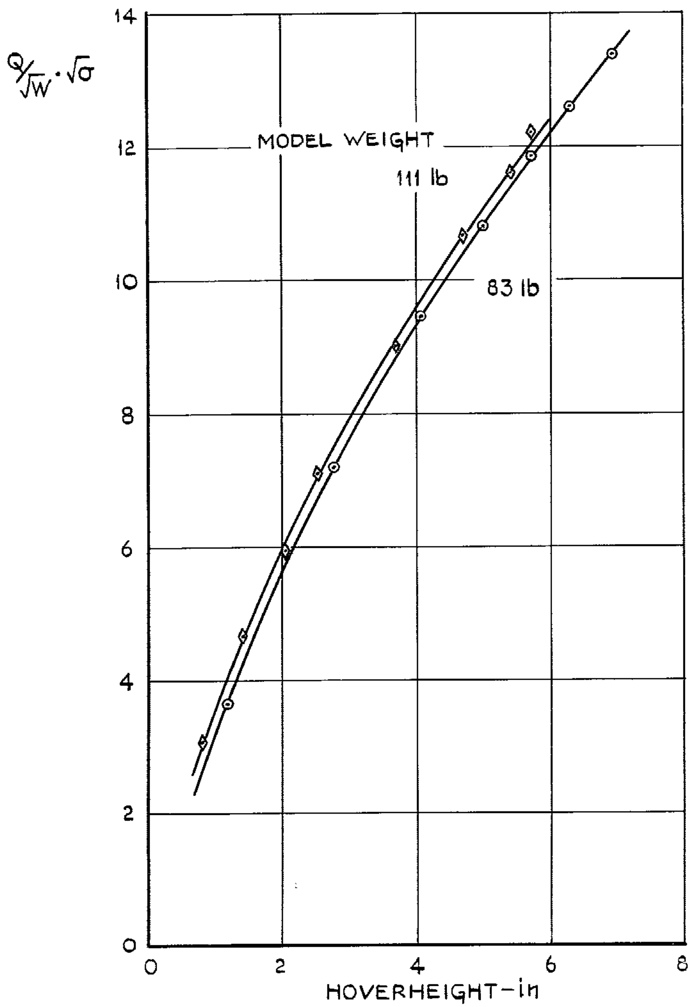


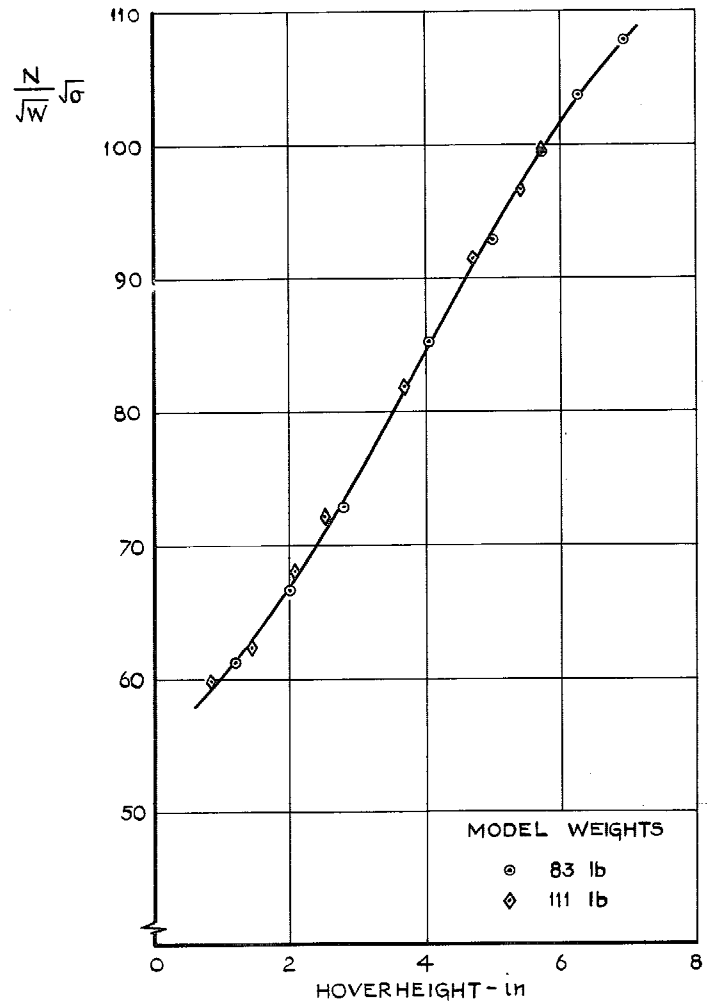
FIG. 7. Change of power with hoverheight.

FIG. 8. A flexible model on the test rig.



FLEXIBLE MODEL

FIG. 9. Change of volume flow with hoverheight.



FLEXIBLE MODEL

FIG. 10. Change of r.p.m. with hoverheight.

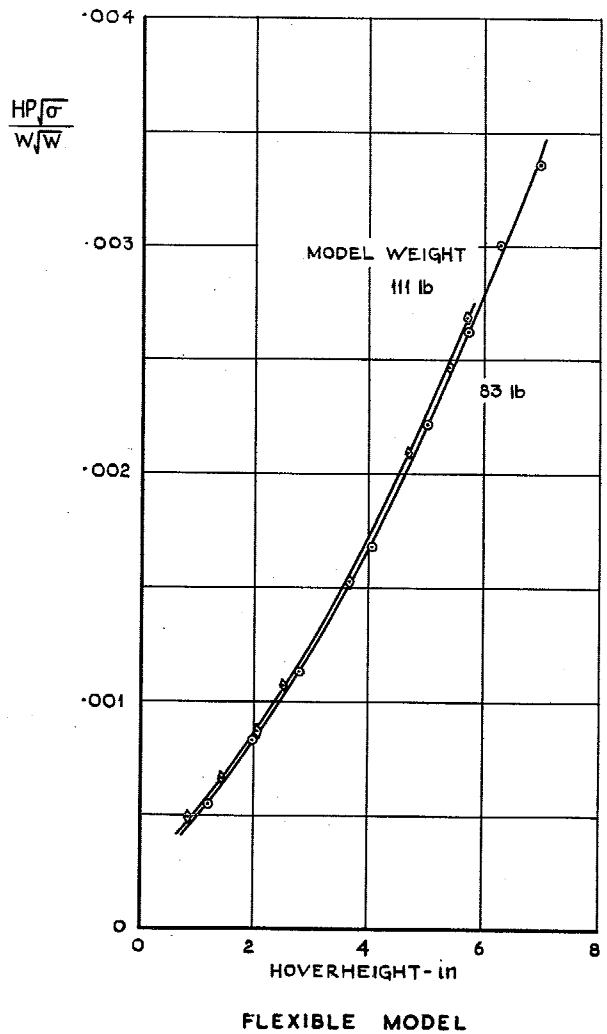


FIG. 11. Change of power with hoverheight.

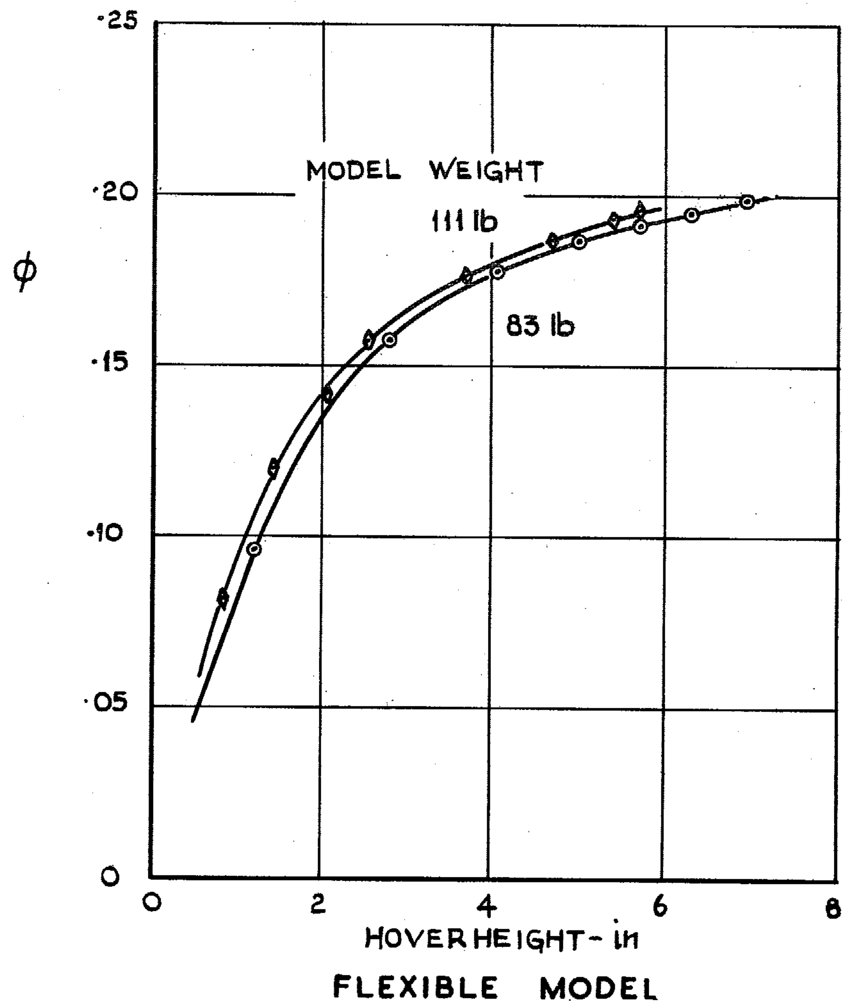


FIG. 12. Change of ϕ with hoverheight.

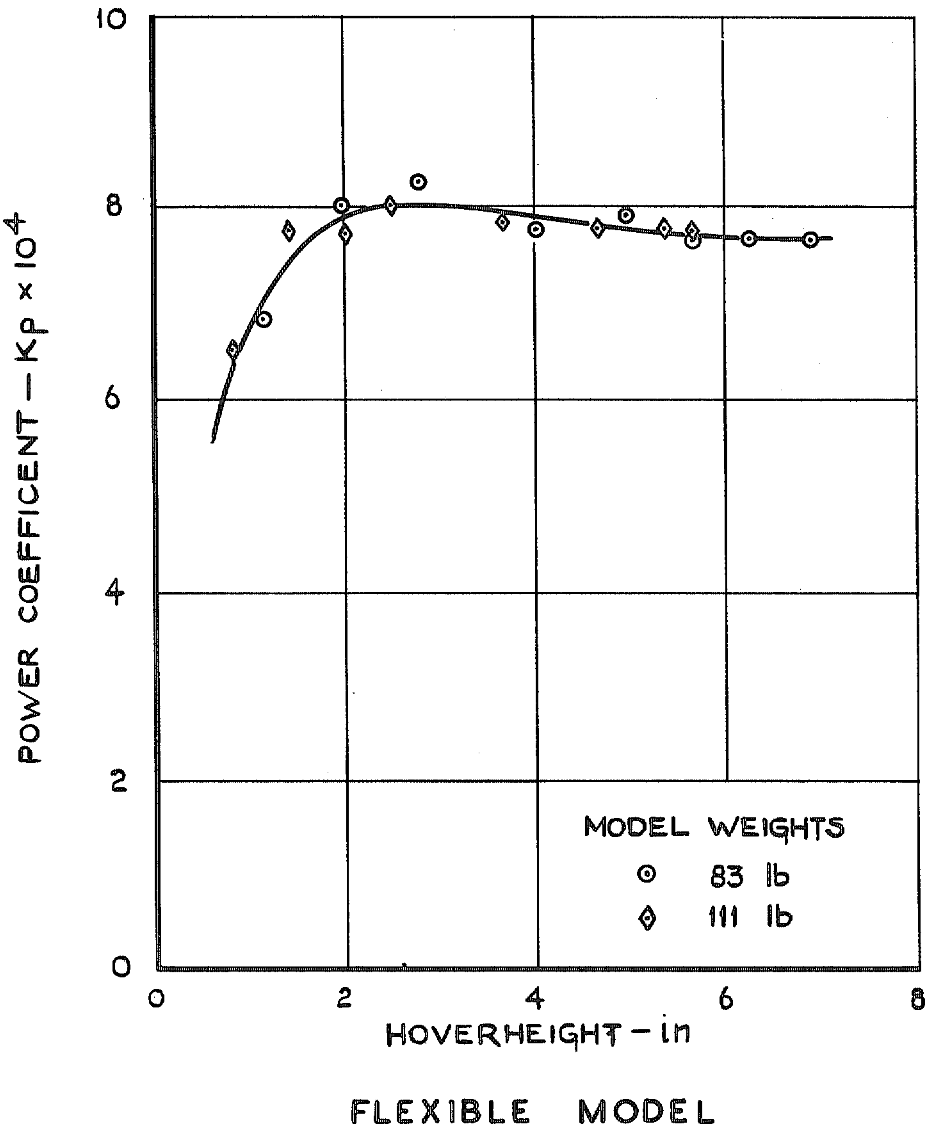


FIG. 13. Change of K_p with hoverheight.

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