

Control, Response and Crash of HMA R.101

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Abstract

The equations of motion of the R.101 airship, as derived and applied by the National Physical Laboratory in simulating the airship's disaster for the Court of Inquiry in 1930, are used to illustrate some aspects of the airship's stability, control and crash. The ship proved to be quite able to recover from the loss of one (or more) gas bags. It is shown that the airship's first dive was caused by the failure of the forward gas bags, from which it was recovering when the elevator cable broke. The crew successfully attempted a soft landing, but a fire subsequently destroyed the ship and all aboard except for six of the crew. It was always known that the elevator cable broke, but the Court of Inquiry thought it happened during the subsequent fire and could not be a cause of the crash. Consequently, the NPL was unable to show that the airship impacted the ground at the expected angle of $15 - 25^\circ$ nose down. The computations made here demonstrate that such an impact is possible if the elevator cable broke as the airship was pulling out of the first dive. It is the simplest explanation of the tragedy that fits the known facts.

1. Introduction

In their work on modelling the behaviour of the R.101 airship during her final and fatal descent, the National Physical Laboratory made wind tunnel measurements of the lift, drag, lifting moment and damping forces on a model of the airship and used these in solving the relevant equations of motion^{1,2}. They used a 20-inch slide rule, tables, and graph paper and consequently it was a very tedious and long calculation that they nevertheless repeated fourteen times. The equations and methods they adopted were designed to save computational effort. Although the Court of Inquiry was satisfied that they had adequately reproduced the ship's last moments the NPL engineers and scientists did not share this view^{3,4}; they thought something had been missed.

In this paper the NPL model and wind tunnel measurements are programmed on a laptop computer and are used to illustrate the airship's control, stability and final crash. Calculations are shown to illustrate:

- Leaving the mooring mast and accelerating to cruising speed.
- Normal elevator response at cruising speed.
- Reversed elevator response at low speed.
- Response to sudden change in pitch, wind speed or thrust.
- Equilibrium conditions for various degrees of heaviness.
- Equilibrium conditions for the loss of lift from a failed gas bag.
- Landing.
- Her fatal crash.

The R.101 came down in two dives. In a previous paper⁵ it was shown, based on evidence from the wreck, that the second and fatal dive was due to the failure of the elevator cable; a failure known to the Court of Inquiry but thought by them to have occurred in the hydrogen fire after the crash and which could not, therefore, be the cause of the crash⁶. The origin of the first dive was taken, in the previous paper, to be the rapid leakage of gas from gas bag 3, but here it is assumed that gas bags 1 and 2 (which were connected) were responsible. This is now believed to be more likely because the outer cover had been renewed everywhere except at the nose around these two gas bags.

2. The National Physical Laboratory Model

Figure 1 shows the forces and moments acting on an airship and the unusual sign convention adopted by the NPL. The drag is XV^2 , the lift ZV^2 , the lifting moment MV^2 , and V is the resultant velocity of the airstream. The values of X , Z and M were tabulated by the NPL⁷ for a velocity of 1 ft/s and vary with elevator angle and pitch angle; they are assumed to increase as the square of resultant velocity V . The lifting force F acts through the centre of buoyancy and is usually balanced by the ship's mass, mg , acting through the centre of gravity and a distance d below it. The quantity $mg d$ is usually called the static moment, M_s . During flight the ship may be light (lift exceeds mass), due to consumption of fuel or dropping ballast, or heavy (mass exceeds lift), due to rainwater on the cover or loss of gas from the gas bags. The general heaviness is indicated by w , acting at the centre of gravity. The particular heaviness, P at distance k from the centre of buoyancy, may be due to the loss of gas in one or more gas bags.

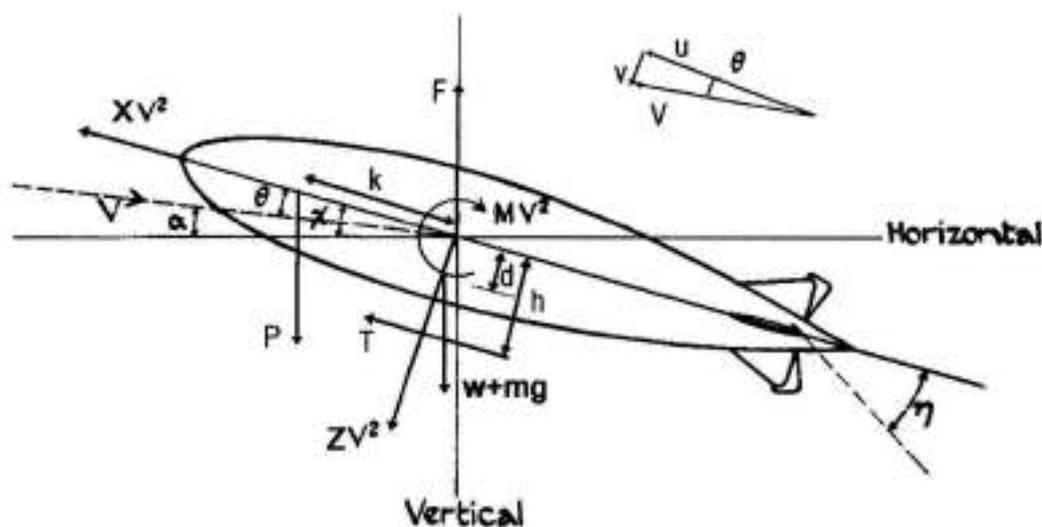


Figure 1 Forces, moments, and geometry of an airship.

The airship moves in still air with axial velocity u along its axis and velocity v across its axis. The airship's direction of motion is α from the horizontal and the incidence is θ , so the central axis is $\alpha + \theta$ from horizontal. The elevator is η from the central axis and the positive direction corresponds to down elevator. Propeller thrust T is parallel to the central axis and

distance h below it. Thrust values were determined by Professor Bairstow⁸. Note that the positive directions of all these quantities are as drawn in Figure 1, and thus the tabulated values of drag X and lift Z are negative, and up elevator is a negative angle.

The equations for motion used by the NPL and their wind tunnel measurements are displayed in Appendix A. They have been programmed using MathCad and were solved using a fifth order Runge-Kutta method using a step length of 0.01 s. The step length originally used by the NPL was typically 1-2 s. Run time on the computer was usually a few seconds only, so many variations could be tested, and the airship's stability, response to controls, and the possible causes of the crash could be investigated.

The lift and drag forces follow the convention used by the NPL in 1930 and are the opposite of modern convention, and the ship moves at α degrees to the horizontal in still air.

2.1 Take off

It was usual for take-off to be made when the airship was statically light ($w < 0$) and may be made with the airship trimmed nose down, neutral, or nose up. Trimming a few degrees nose down has the slight advantage that when the propeller thrust is increased to reach cruising speed, the airship may take up a horizontal position and hence attain minimum drag and maximum speed. Of course, when take-off is in neutral trim or nose-up then the airship may be re-trimmed in flight by pumping ballast forward.

Figure 2 shows a possible take off sequence for R.101. In this case the ship is in neutral trim and when released from the mast it is made 1-ton light by dropping ballast fore and aft. When sufficiently clear of the mast the propeller thrust is increased to 10 % of cruising-thrust. This causes two or three damped oscillations in pitch angle, but of less than 1° amplitude. After 200 s the ship has risen by 800 ft and speed has increased to about 15 ft/s (10 mph). The elevator is set to its equilibrium value for cruising speed (1.87° up) and thrust is increased to 100%. This results in a pitch oscillation to 3.5° before it settles at about 1.3° nose down. The Captain may well consider it better, from the passenger's point of view, to increase thrust more gently than assumed here. Cruising speed is reached at 600 s by which point the altitude has risen by about 1,180 ft. As the mast is 200 ft above the ground, and the mast itself well above sea level, the ship could be cruising at about 1,500 ft above sea level. Thus, the airship could reach cruising altitude and speed within 10 minutes of casting off, although it may be considerably longer than this in practice.

Of course, the elevator angle for equilibrium flight may not be known and the height coxswain would need to approach the correct value by trial and error. Figure 3 shows the effect of setting the elevator 1° above or below the equilibrium value. If the elevator is set 1° below equilibrium value (-0.87°) at 200 s, then the airship continues to rise under the influence of the increased thrust but eventually reaches a maximum height and then begins to fall. By increasing the elevator gradually, the height coxswain can gradually approach equilibrium. If the elevator is set 1° up from equilibrium (-2.87°) then the airship continues to rise, and the coxswain must reduce the elevator as he approaches the appropriate height.

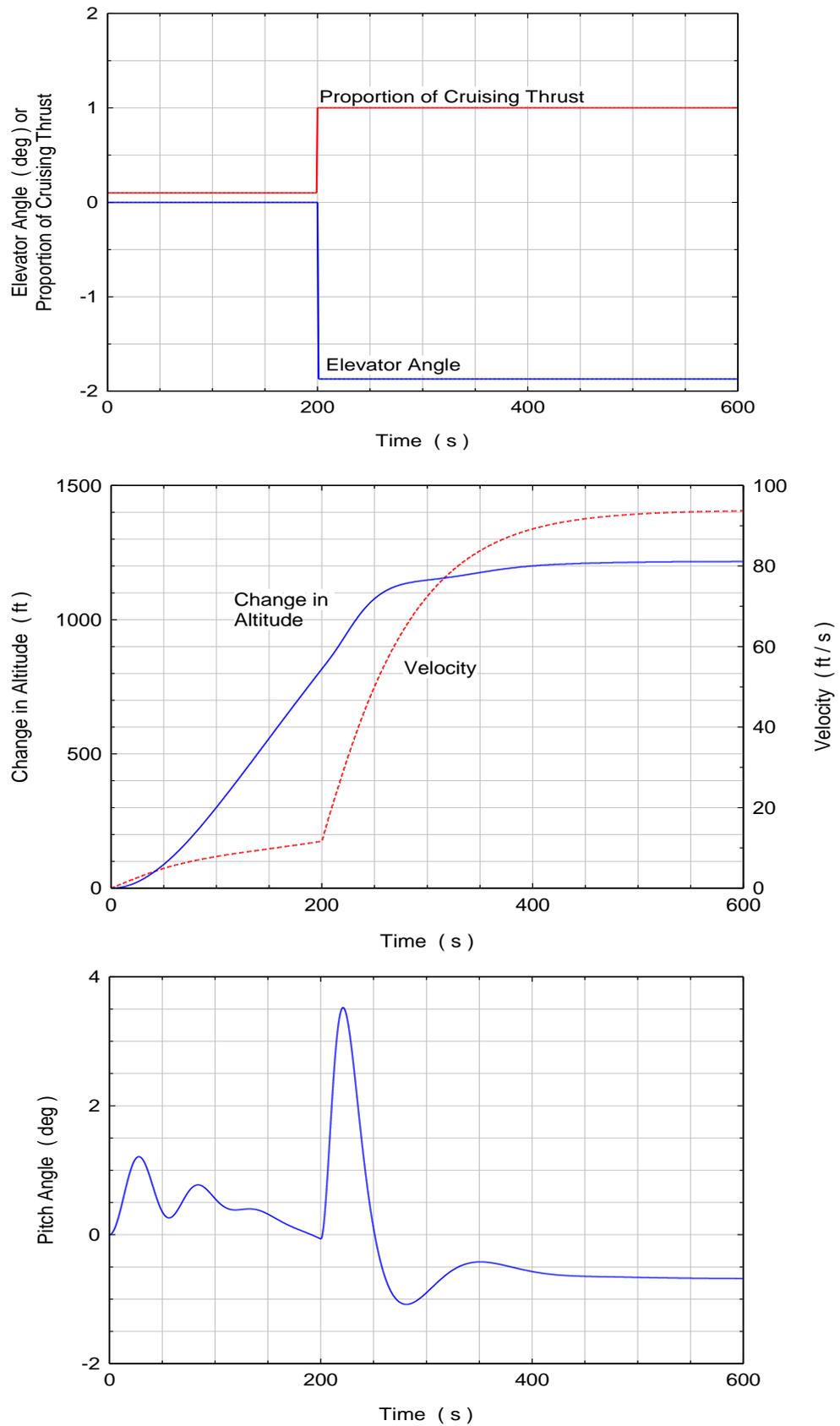


Figure 2 Leaving the mooring mast. 1-ton general lightness, 0° initial pitch angle, Elevator angle and thrust (top), altitude and forward velocity (centre), pitch angle (bottom)

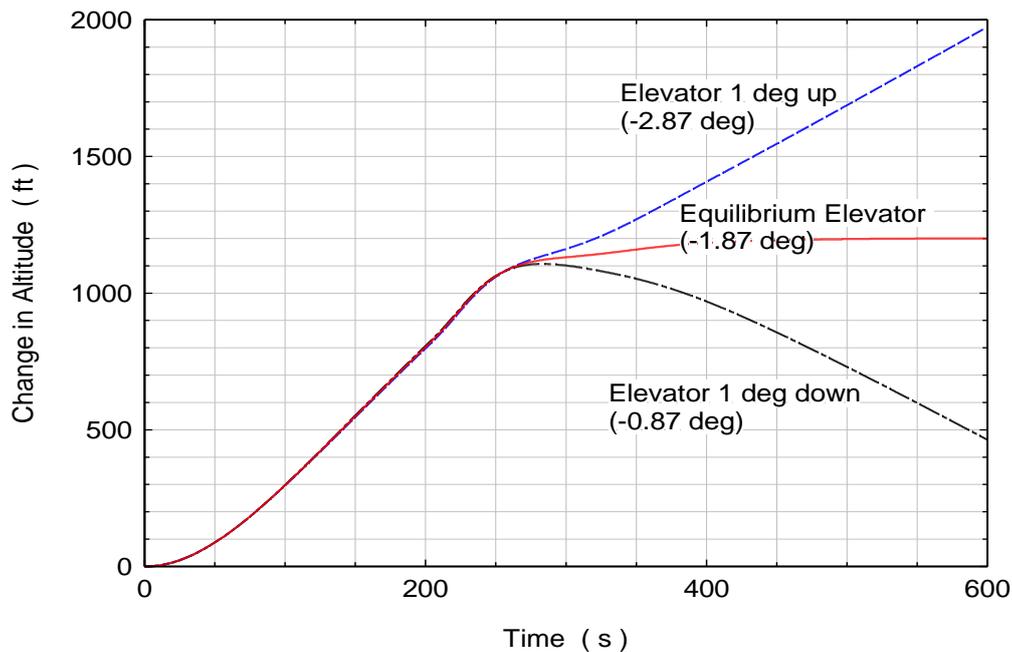


Figure 3 Showing influence of elevator on altitude.
 Equilibrium elevator -1.87° , airship 1-ton general lightness.
 10 % cruising thrust for $t < 200$ s, 100% cruising thrust for $t > 200$ s.

Clearly, the airship is in a state of unstable equilibrium in that a small increase in the equilibrium angle of the elevator increases both the lift and the lifting moment, and without a corresponding increase in restoring forces and moments the airship rises continuously. The same happens when the elevator is decreased. Unstable equilibrium is the usual condition for airships, but it presents no problems and is readily controlled by the height coxswain.

2.2 Response at cruising speed to changes of elevator

The pitch and roll of airships are independent of each other and consequently they are controlled from two independent helms, as shown in Figure 4. It was normal for the height coxswain to stand along the ship's longitudinal axis, although, in R.101, this did not make it convenient for him to view the altimeter.

The airship's response to an increase or decrease in elevator position, relative to its equilibrium setting, is illustrated in Figure 5. Two responses are shown, corresponding to sudden increases of 2° up or down and 4° up or down, each lasting for 50 s. In practice, the fastest speed with which the elevator could be moved was stated to be 1 degrees/s^9 , but for our



Figure 4 Control room of R.101 looking forward and showing the two helms, instrumentation, and speaking tubes (National Archive, Kew)

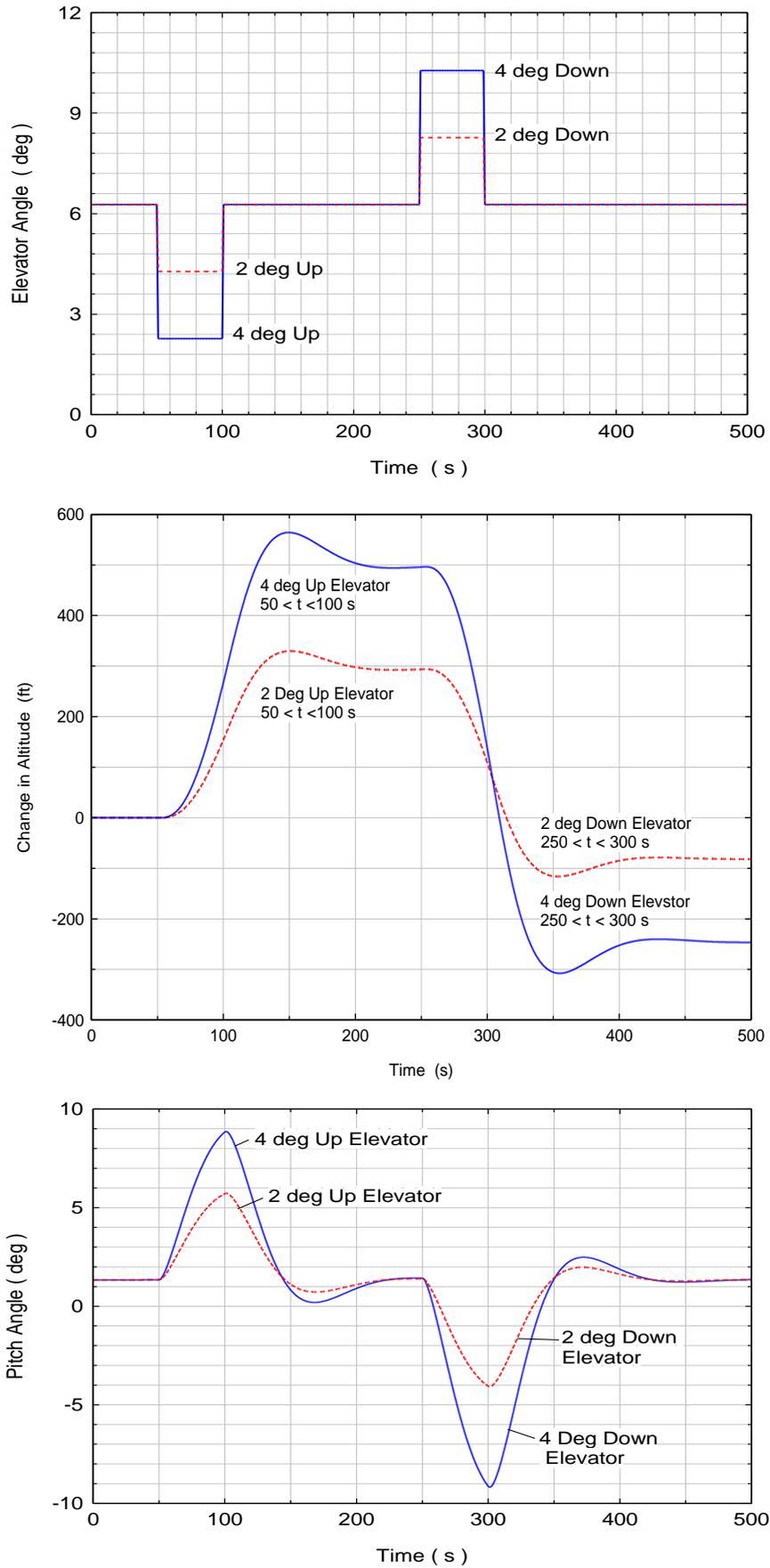


Figure 5 Response of R.101 to step changes in elevator relative to equilibrium flight
 Top: elevator angle (up elevator is negative), centre: change in altitude, bottom: pitch angle

purposes a step change is more convenient. The airship was assumed to be at cruising speed and 4 tons heavy, hence the equilibrium setting of the elevator is 6.3° down with a pitch angle of 1.3° up. The Court of Inquiry commented on the apparent anomaly of a heavy ship flying with the elevator trying to put the nose down, but they were assured that this was normal for a ship in horizontal trim¹⁰.

The first 50 s of Figure 5 confirm equilibrium conditions. At 50 s the elevator is put up by 2° or 4° and is returned to equilibrium at 100 s. This results in a corresponding increase in altitude of 250 ft or 450 ft by about 200 s and corresponds to a time lag of about 150 s. As might be expected, large airships respond slowly to controls. Nevil Shute Norway¹¹, the novelist and chief calculator in the design of the R.100, found this very comforting and he remarks that in the control room of R.100

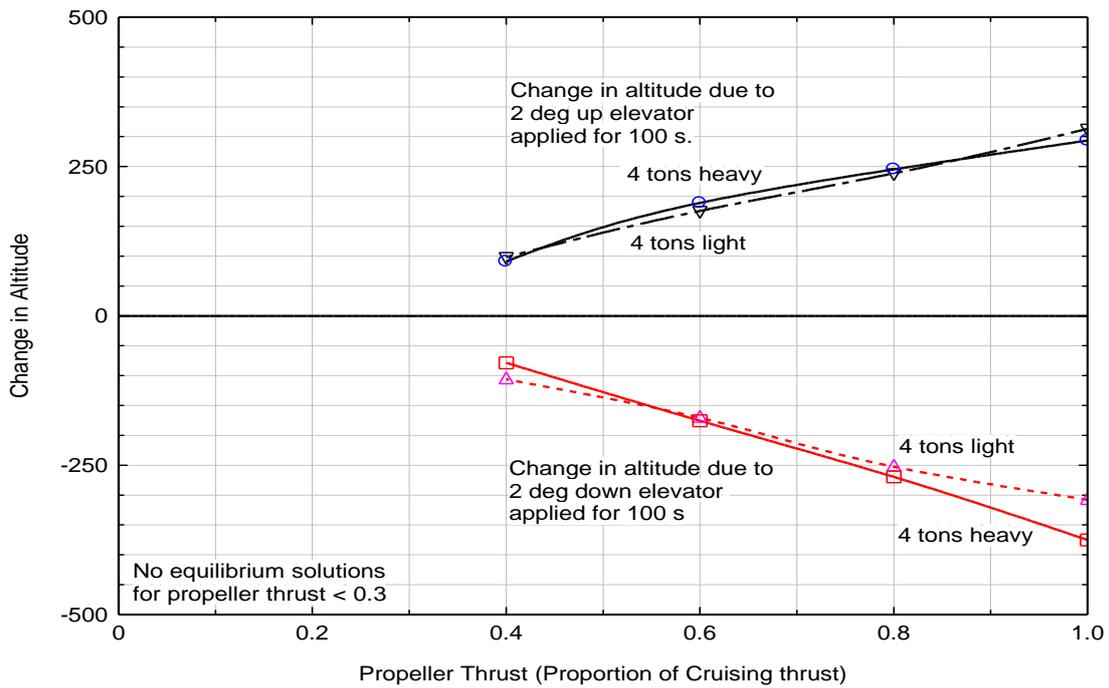
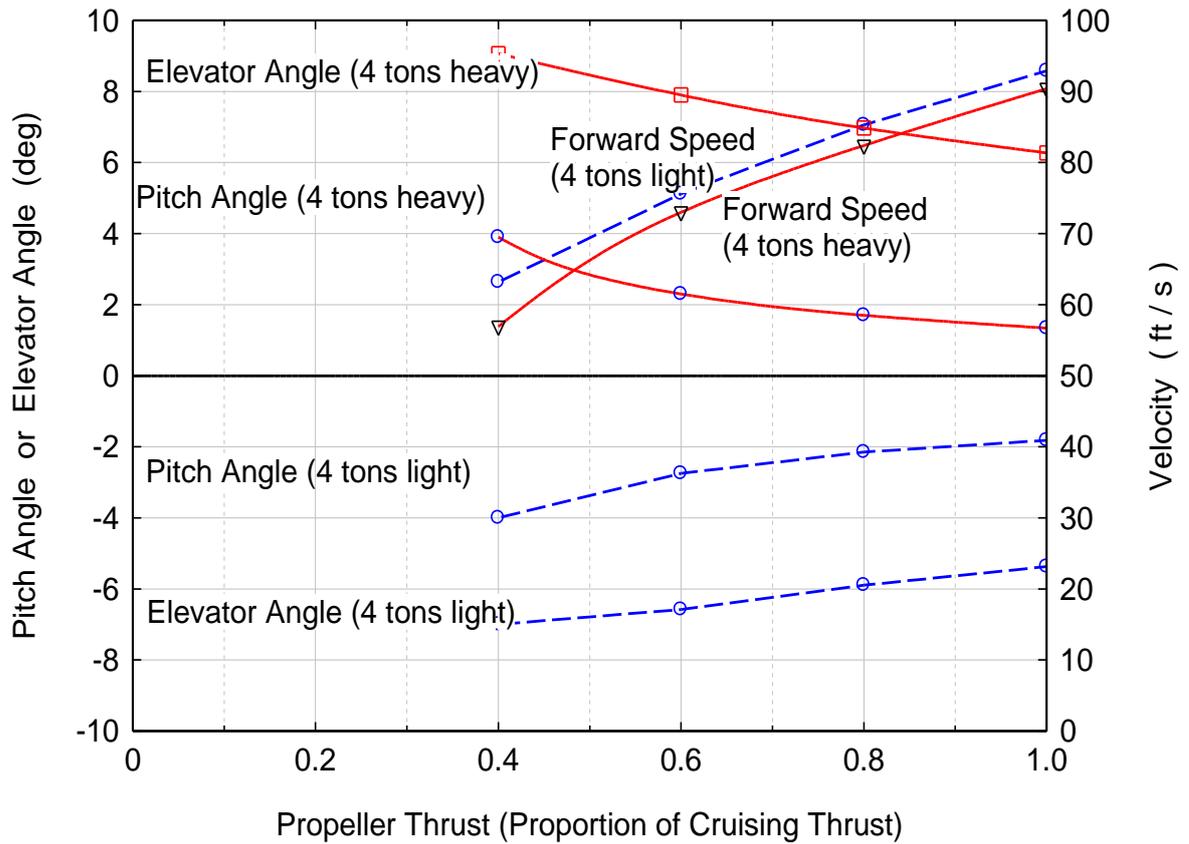
“there was time for a little conference between the officers over each movement of the controls I do not think it was ever necessary to make a quick decision in the way that a pilot of an aeroplane has to;”

The increase in altitude resulting from up elevator slightly overshoots the steady state value, but the oscillation is quickly damped out.

At 250 s the elevator is put down 2° or 4° and the airship returns to equilibrium at about 400 s. This initiates a loss of height, but the airship not only descends to its initial altitude but descends to 90 ft or 240 ft below it. Had the airship been perfectly symmetrical then it would have returned to its initial altitude, but the protrusions of the control cabin and the five engine pods beneath the outer cover disturb the airflow on the underside of the ship resulting in an increased underside drag and a greater change of altitude when descending. Throughout these manoeuvres the airspeed remained between 90 and 91 ft/s.

2.3 Elevator Response at Reduced Thrust

The response of the airship to changes in elevator when travelling at reduced thrust is plotted in Figure 6. The top graph shows the equilibrium elevator angle and pitch angle, plotted against thrust (expressed as a proportion of cruising thrust) for a general heaviness of 4 tons or lightness of 4 tons. The lower graph shows the corresponding gain or reduction in altitude, assuming the elevator is raised or lowered for 50 s. At low thrust, usually below about 30%, equilibrium is not always possible, and results are not shown. Such instability is not too inconvenient for the coxswain because, as Figure 3 illustrates, equilibrium flight is always unstable and needs just as much attention.



2.4 Reversal of Elevator Control at Low Speed

The US Technical Manual of Airship Aerodynamics¹² notes that there is a curious paradox in the control of airships at low speeds.

“If the speed falls below a certain definite value known as the ‘reversing speed’, control becomes reversed and pulling up the elevators causes the airship to descend, although it turns nose upward.”

This reversing speed is about 15 mph for most airships. The manual goes on to explain that at low speeds the dynamic forces and moments (proportional to the square of velocity) are insignificant in comparison to the static restoring force due to the weight when the airship is inclined. When the elevator is pulled up the lifting moment causes the nose to rise but the large static moment restricts this to a small angle. If this angle is small enough, the dynamic up force on the nose will be less than the dynamic down force on the elevator and the airship will descend with its nose up.

This reversal of the elevator control is particularly apparent if the airship is trimmed nose heavy. It leads to a serious situation when landing if, due to loss of superheat, the airship becomes statically heavy and starts to descend. If the speed is below the reversing-speed, then application of the up elevator simply causes the rate of descent to increase, possibly with embarrassing results. The advice of the Technical Manual in this situation is to drop ballast, increase speed to a value above the reversing speed, or reverse the rotation of the propellers to cause the airship to ascend with its nose down.

Reversed elevator control is illustrated in Figure 7 when the airship travels at about 20 ft/s (13.6 mph). Three cases are illustrated, namely,

- equilibrium flight for 200 s,
- equilibrium flight for 50 s after which the elevator is raised by 20° ,
- equilibrium flight for 50 s after which the elevator is put down 20° .

If the elevator is put up at 50 s then the nose rises to about 1.5° and at about 100 s the airship starts to fall rather than rise; at 200 s it has fallen about 35 ft. Similarly, if the elevator is put down at 50 s then the nose pitches down by about 1.5° but the airship rises by about 40 ft at 200 s. Such reversals can be dangerous when the airship is manoeuvring close to its mooring mast.

The pitch oscillation in Figure 7 (centre) appears to have the characteristics of a well damped short period oscillation but with the frequency of a phugoid for heavier than air machines. This would benefit from further investigation by determining the eigenvalues of the relevant Jacobian matrix/determinant.

2.5 Response to Changes in Pitch

Changes in pitch angle may be caused, for example, by a sudden gust of wind which may raise or lower the nose and Figure 8 reveals the R.101's response to a sudden increase or decrease in pitch angle of 1° . The ship is at cruising speed and 1-ton light and consequently for equilibrium flight the elevator is 0.68° up and the pitch is 1.3° nose down. At 50 s in Figure 8, if the pitch changes suddenly by 1° up then it continues to rise by a further 1° before falling back and overshooting its equilibrium value slightly before settling. Accordingly, the response is stable, that is, a small deviation from equilibrium is automatically returned to equilibrium. The same happens, but in reverse, when the pitch angle suddenly decreases by 1° .

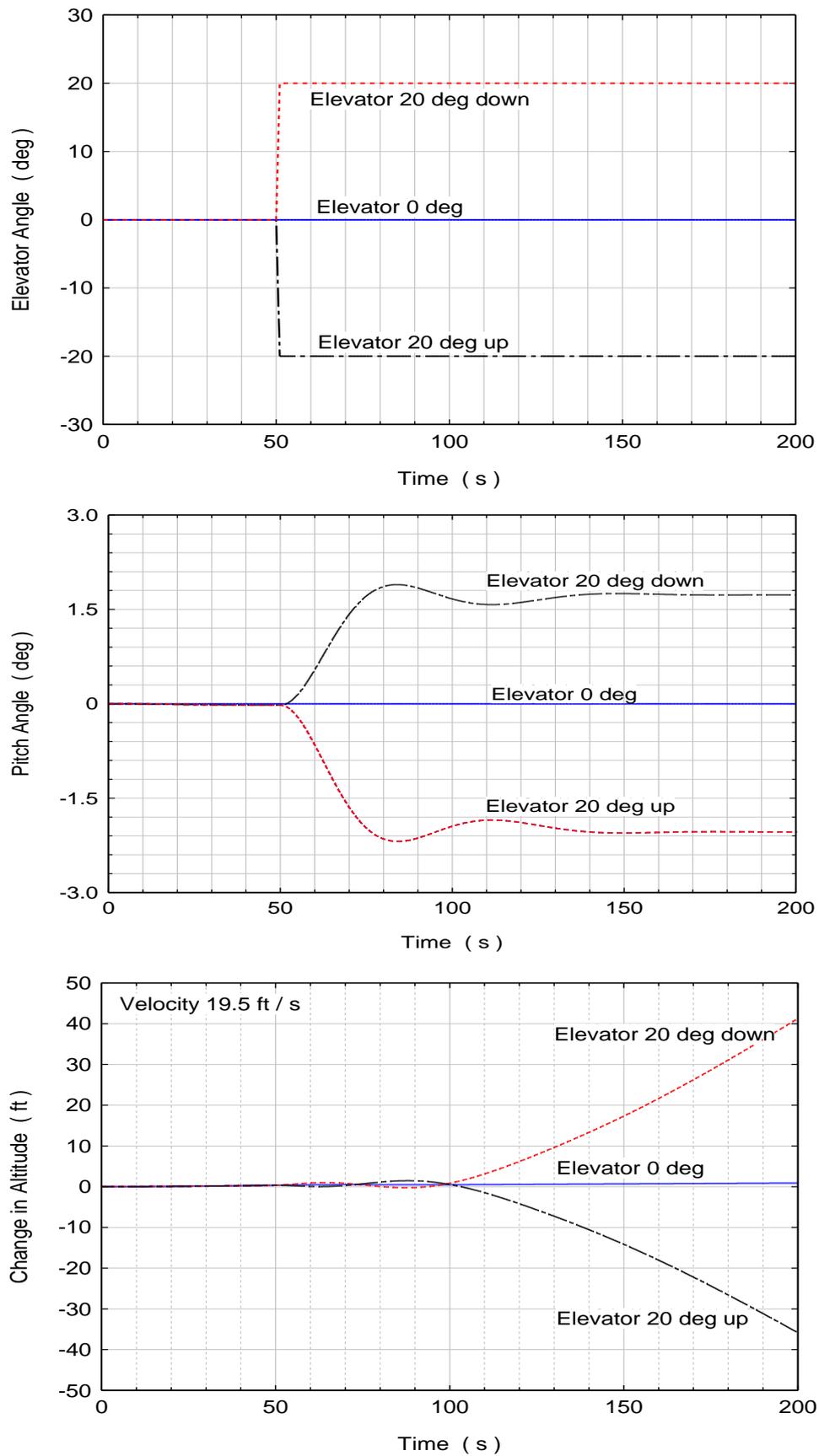


Figure 7 Reversal of elevator control at low speed
 Top: elevator position, centre: pitch angle, bottom: change in altitude
 Ship 4 tons heavy, 3% of cruising thrust, speed 19.5 ft/s.

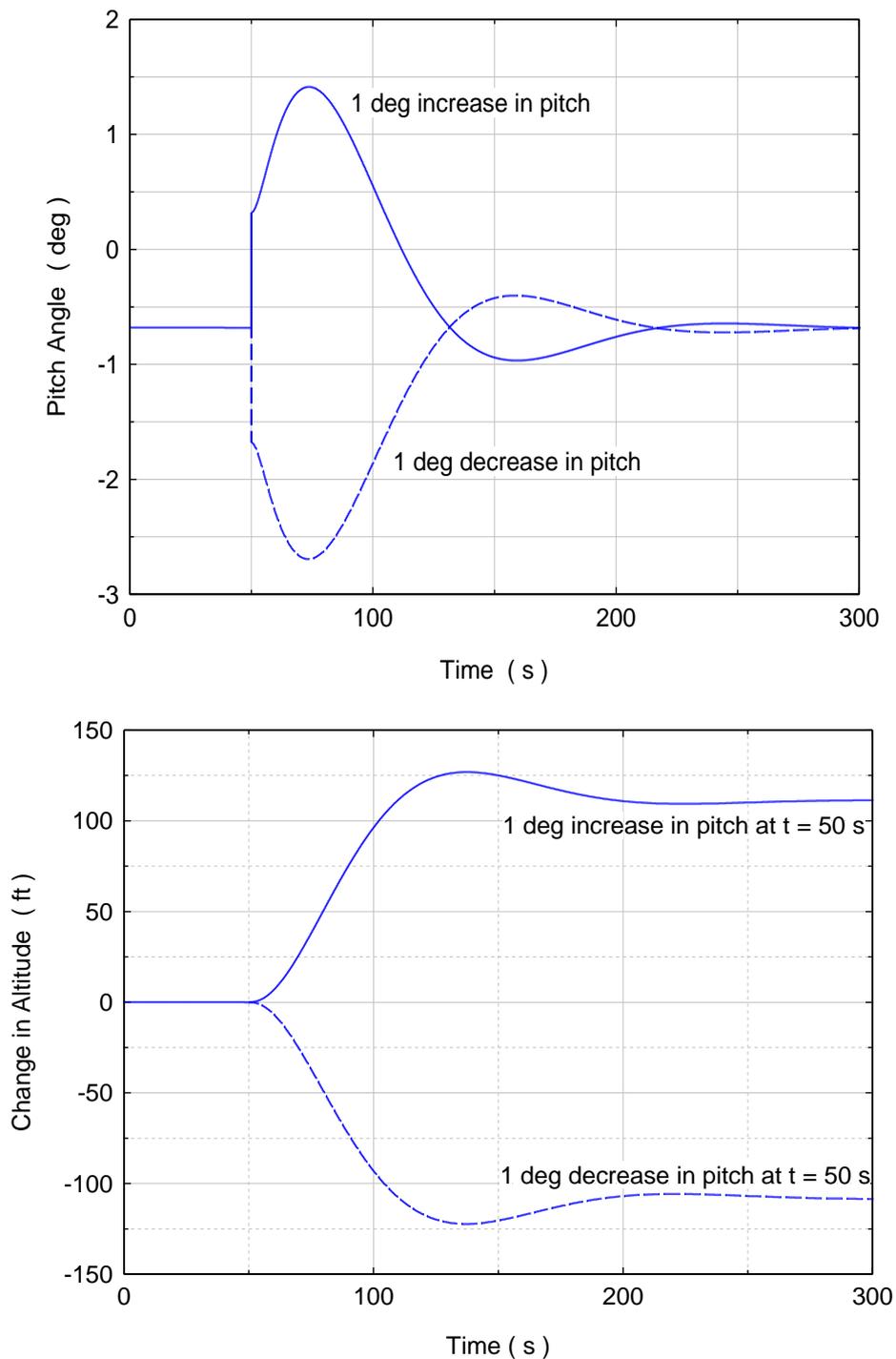


Figure 8 Response to a step change in pitch of 1° up or down
Top: pitch angle, bottom: change in altitude

However, there is a net gain in altitude of about 115 ft when the pitch increases by 1° and a loss of about 103 ft when the pitch decreases by 1° . But even though the response is stable the height coxswain will probably wish to counter the changes by use of the helm, so the ship retains a steady altitude and the passengers are not discomforted too much.

2.6 Response to Changes in Wind Velocity

A sudden change in wind velocity may occur when an airship flies into a gust of wind. Such gusts are usually of a temporary nature. But for demonstration it is assumed that the sudden increase in wind speed is constant in magnitude and lasts for several minutes (wind shear). In Figure 9 the airship is 1-ton light and is in equilibrium at a cruising speed of about 94 ft/s. If there is a sudden increase in wind speed from ahead, then the air speed increases momentarily to 104 ft/s before returning to equilibrium. Similarly, if the sudden increase is from the rear then the air speed changes momentarily to 84 ft/s and the reduced drag enables the airship to accelerate to its equilibrium speed of 94 ft/s by 350 s. Thus, the airship always tries to return to its equilibrium velocity. However, there is a change in altitude of about 44 ft when the head wind increases by 10 ft/s and a loss of about 50 ft when the head wind reduces by 10 ft/s.

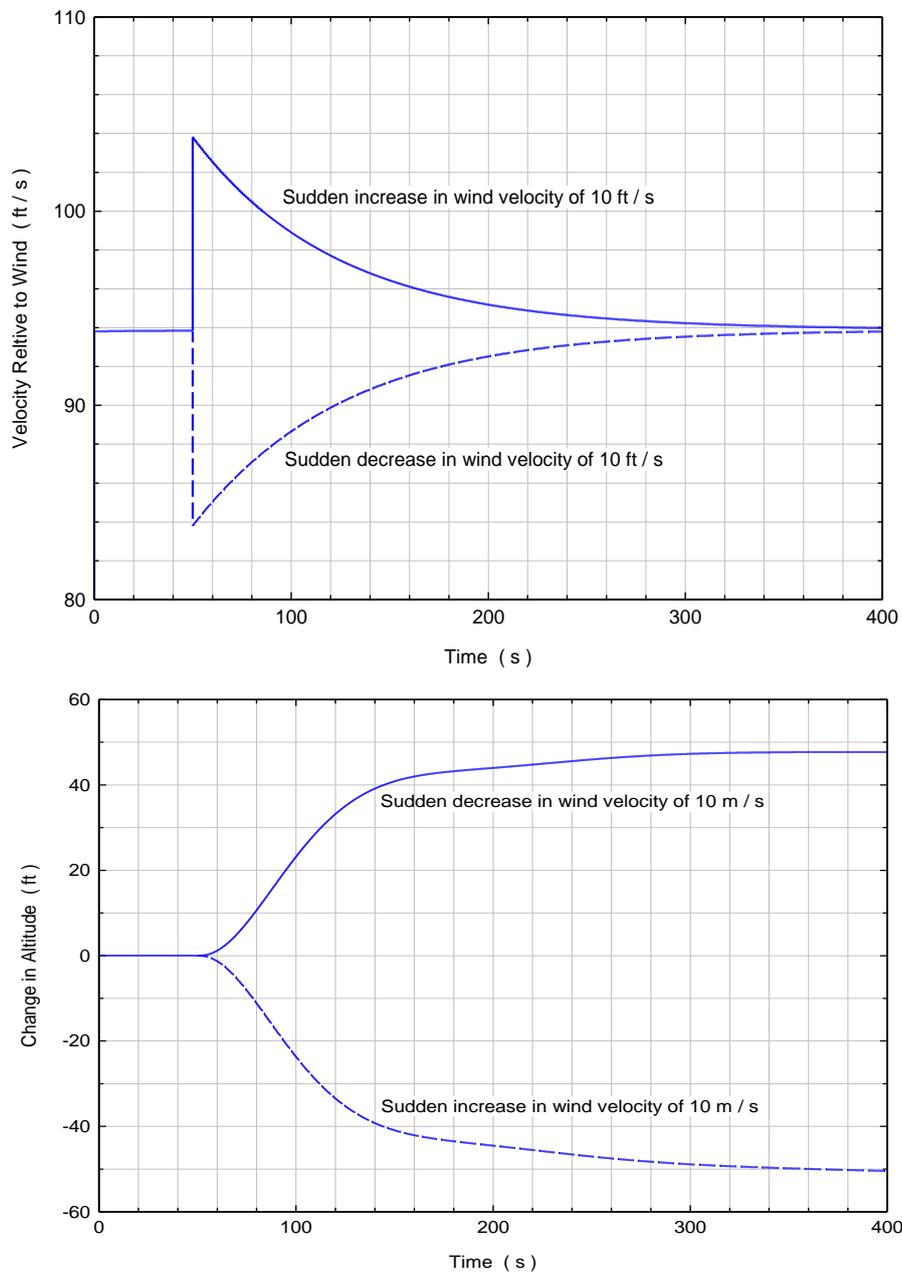


Figure 9 Response to a step change in headwind velocity of 10 m/s
Top: Velocity relative to the headwind, bottom: Change in altitude

Squadron Leader Booth, Captain of the R.100 when she crossed the Atlantic, gave evidence to the Court of Inquiry¹³ that during their crossing they experienced winds of 30 mph (44 ft/s), but as they were over the sea there was little turbulence and little difficulty in keeping a constant altitude. Essentially the wind velocity was constant and horizontal. He thought that when travelling over land in normal bumpy weather, the height coxswain would have greater trouble but should, nevertheless, be able to keep the airship within 250-300 ft of the desired height, and that this might be extended to 400-500 ft under bad conditions. These figures are much greater than those calculated above for horizontal winds. Booth's figures refer to vertical gusts, either up or down, which are more effective in changing a ship's altitude than horizontal gusts and always require action from the height coxswain to maintain altitude.

The importance of vertical air currents was made apparent in the crash of the US airship Shenandoah in September 1925¹⁴. She was the USA's first large airship and was based on wartime Zeppelins. The gas bags of rigid airships are usually only partly full at take-off and as they rise, and air pressure falls, the gas expands until at a certain altitude, called the pressure point, the gas bags are fully inflated. Further increase in altitude creates a pressure difference between the gas and the atmosphere and would rip open the bags. To prevent this, automatic pressure relief valves are fitted to vent the excess pressure. However, if the rate of rise is very large, as it was with the Shenandoah, then the gas does not escape quickly enough from the bags and they will burst, reducing lift and possibly bringing down the airship. To avoid this, the automatic valves of R.101 were made sufficiently large to cope with the expected rate of rise. Additionally, an entirely new and ingenious valve system was used. On either side of the gas bags, about half way up, the valves were fixed and opened with a very small pressure difference (2 mm water) against a very light spring force, possibly too light because the valves often opened when the ship rolled. They were, however, designed to pass 72,000 cubic feet of air per minute, and could cope with an ascent rate of 4,000 ft/min (67 ft/s) which is almost three times that which destroyed the Shenandoah.

3. General Heaviness and Loss of Gas Bags

Airships normally flew with some degree of general heaviness or lightness because a perfectly balanced ship is difficult to control. Also, of course, the balance of weight and lift continuously changes during flight because fuel is used by the engines, the cover may become heavy during wet weather, and the gas may leak from the gas bags. It is of some interest to know what degree of heaviness a ship can sustain, and equally, if she can survive the deflation of one or more of her gas bags.

The conditions for equilibrium are specified in the Appendix (Equations A1, A5 and A6). The solution of these three implicit equations involves a double iteration and is very tedious without the aid of a computer. Thus, Professor Bairstow, in his submission to the Court of Inquiry, did not solve these equations but presented a graphical method which enabled him to show that the maximum heaviness that R.101 could sustain was about 14 tons. Dr Eckener, based on his extensive experience, thought this was reasonable.

The equilibrium conditions for R.101 with various degrees of heaviness or lightness are displayed in Figure 10 (top). When the airship is 10 tons heavy the elevator must be put up to about 5°. This raises the nose by about 13° and the lift so generated compensates for the heaviness. Of course, the cruising speed falls to about 80 ft/s. As can be seen, heaviness more than about 14 tons requires large increases in elevator and corresponding increase in pitch, which results in a rapid fall in speed and a loss of aerodynamic lift, such that the increased heaviness cannot be supported beyond this value. Similar behaviour is observed when the airship becomes very light.

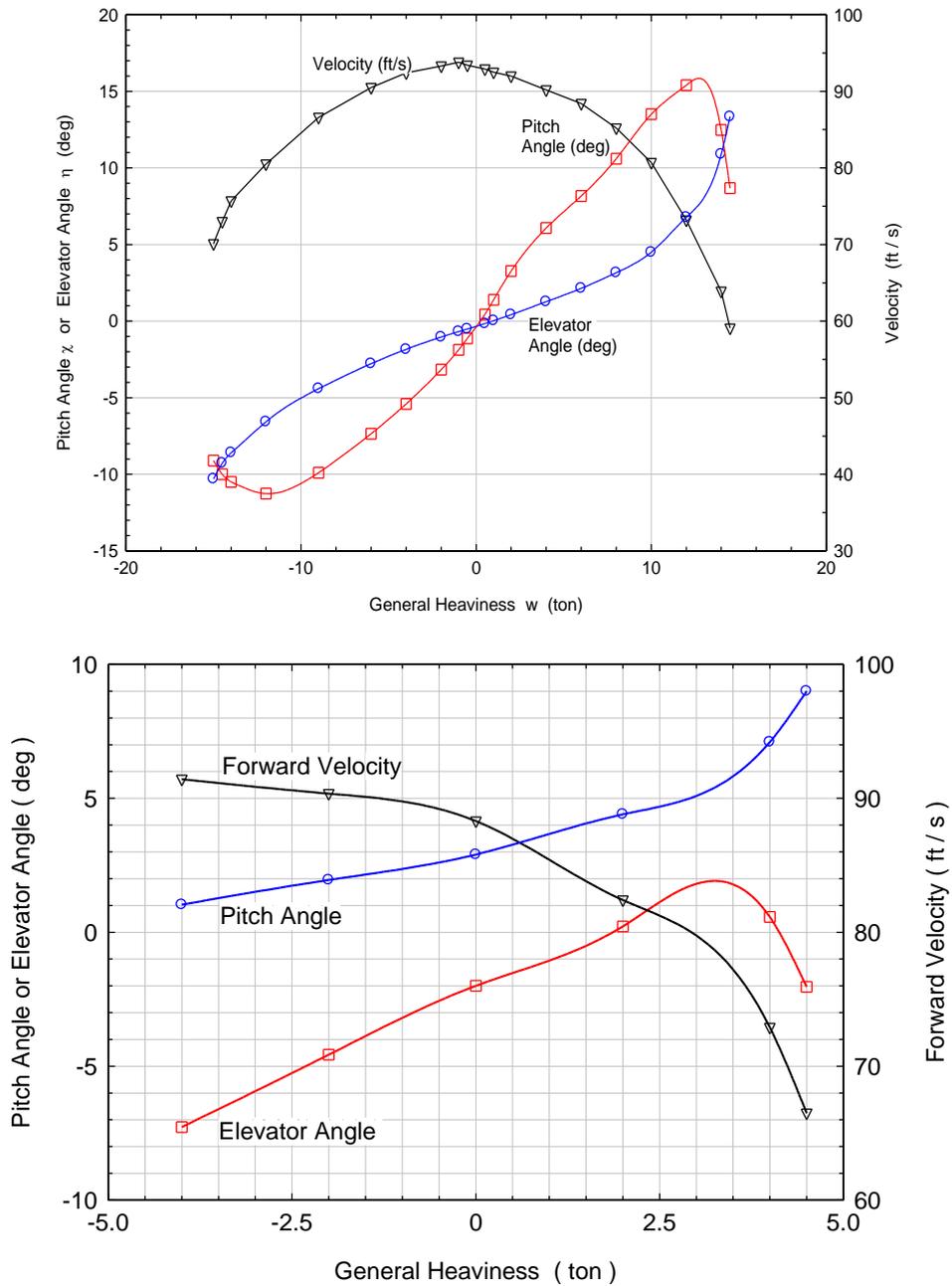


Figure 10 Top: influence of general heaviness on pitch angle, elevator angle, and velocity for equilibrium flight at constant altitude ($P=0$)
 Bottom: as in the top figure, but with gas bags 1 and 2 burst and empty

In these calculations the particular heaviness (P) is assumed to be zero, but if a gas bag fails and its contents escapes then the corresponding loss of lift defines the value of particular heaviness and the position of the gas bag defines the distance, k , from the centre of buoyancy. Figure 10 (bottom) shows the equilibrium conditions for the loss of all the lift from gas bags 1 and 2, which are connected. This amounts to 4.2 tons at a distance of 293 ft forward of the centre of buoyancy.

Clearly the airship could survive such a particular loss over a wide range of general heaviness, from 5 tons light to 4.5 tons heavy. The cruising speed when 4.5 tons heavy would be quite low (about 66 ft/s) and the fastest speed would require the airship to be 5 tons light with an elevator angle of about 9° up. This would produce a very respectable cruising speed of about 102 ft/s.

The equilibrium conditions after the loss of other gas bags are presented in Table 1. The table specifies the gas bag, its loss of lift, and its distance from the centre of buoyancy, together with maximum heaviness that can be sustained assuming that the pitch angle does not exceed 15° and the elevator angle does not exceed $\pm 25^\circ$. Clearly, the R.101 could survive the loss of any one gas bag except gas bags 11, 12, or 13 without dropping ballast.

Table 1 Maximum Heaviness for equilibrium after Loss of a Gas Bag.

Gas bag	Lift P tons	Distance k ft	Equilibrium pitch angle degrees	General heaviness tons	Elevator angle degrees	Velocity ft/s
1&2	4.1	294	15	9.5	-13.3	57.7
3	9.5	247	12	1.6	-23	68.0
4	12.7	198	11	-2.3	-21.6	704.
5	14.4	152	12	-3	-20.3	67.8
6	15.1	109	15	2.5	-25.3	60.6
7	14.5	65.2	15	-0.6	-7.6	59.0
8	14.5	22.5	15	0	-0.2	57.7
8a	15.5	-21*	15	-0.7	9.7	54.9
9	15.2	-67.5*	15	-0.8	20.5	50.9
10	14.9	-117*	15	-1.3	25.4	49.8
11	12.8	-166*	-	-	-	-
12	11.8	-219*	-	-	-	-
13	7.1	-260*	-	-	-	-
14	3.5	-317*	15	10.8	21.3	50.7
15	1.5	-354*	15	13.3	13.0	53.6
16	0.6	-395*	15	14.1	8.5	55.1

* Scaled from drawing.

4. Landing

The author of the *Technical Manual on Airship Aerodynamics*¹⁵ remarks that “the most difficult manoeuvre which confronts the pilot is the landing” and he divides the operation into three parts, namely weigh-off (when the engines are stopped), approach (when altitude and velocity is reduced), and arrival at the landing party [or mooring mast]. The R.101 is shown at its mooring mast in Figure 11. In principle the mooring method was simple. A cable was run out from the top of the mast and as the airship approached she dropped a similar cable from her nose. A small ground crew coupled the two cables together and the ship was drawn to a universal joint at the top of the mast using a motor. All passengers, crew, goods and services were transferred to and from the ship via this connection. Manhandling her into a hangar was required only when major repairs were necessary. Formerly airships always had to be manhandled into their hangar, by a ground crew of up to 500 men, whenever she landed, and on windy days this was a very dangerous procedure.



Figure 11 R.101 at the mooring mast. National Archive, Kew.

Even so, some experience was necessary in the use of a mooring mast. Nevil Shute Norway¹⁶ records that when the R.100 first approached the mast at Cardington after her inaugural flight from Howden where she was built:

“On this first flight it took three hours to land R100 to the mast; three times we had to leave the aerodrome and fly a circuit and come in again and make a fresh attempt to establish a connection between the steel cable dropped from the nose of the ship and the cable from the masthead laid out upon the aerodrome. The mooring system was essentially sound and at the conclusion of the R.100 flights sufficient experience had been gained in the handling of the ship and the use of the mast equipment to enable landing to be made at the mast in about forty minutes, but this result was not achieved without experience of numerous mistakes”

Figure 12 shows a possible sequence of events as the R.100 approached the mooring mast. It is assumed that she was in neutral trim ($P = 0$), 4 tons general heaviness ($w = 4$ tons) and travelling in level flight at constant speed. This is illustrated by the first 50 s of Figure 12. At 50 s the propeller thrust is reduced to 30% of cruising thrust and the elevator put down to 10° to assist in losing height. At 180 s the airship's altitude has fallen from 1,000 ft to 200 ft and velocity has reduced from 91 ft/s to about 50 ft/s. The elevator is set to neutral at 200 s and to reduce the velocity the propeller thrust is reversed during the period $250 < t < 400$ s, after which thrust is set to zero. The effect of this is to slow the airship to about 10 ft/s at a height of 200 ft, which is the height of the mooring mast. The period of reverse thrust may be extended to reduce the speed further. The horizontal distance covered during this manoeuvre is about 1.6 miles for losing height and 1.2 miles for slowing to 10 ft/s, a total of 2.8 miles in 400 s. After this the ship needs to be drawn to the tower and a proper connection made with the airship's nose. Of course, this is only one example and many other scenarios are possible.

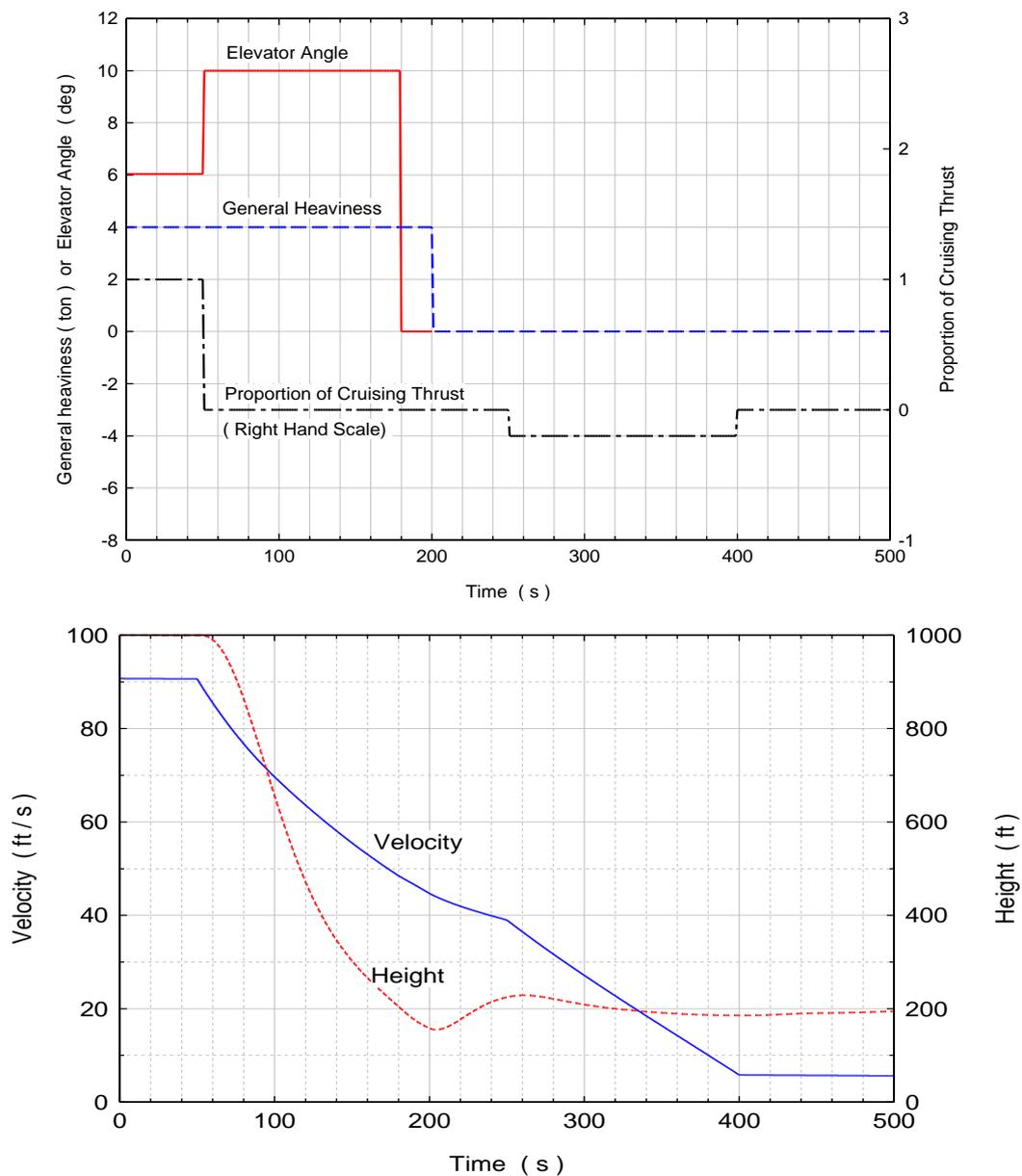


Figure 12 Landing at the mast.

Top: elevator position, general heaviness, and thrust; bottom: altitude and velocity

Further use of the elevator and reverse thrust may be necessary to make a satisfactory junction with the landing party, and the elevator helmsman must remember that he may be travelling slower than the reversing speed when up elevator is used to reduce height and down elevator to increase height.

5. The Final Flight Path of the R.101

The R.101 crashed in October 1930, effectively ending British interest in large commercial airships. The subsequent Court of Inquiry¹⁷ concluded that the crash occurred in two phases or dives. The first dive was caused by the ripping of the outer cover in a 30 mile/hour or more wind which damaged one of the forward gas bags causing a significant loss of lift. The airship was pulled out of the subsequent dive by a rapid application of the up elevator. The cause of the second dive, a few seconds later, was unclear but was attributed to the decision to make a soft landing by dropping all available ballast and stopping the engines. This was stated to be the correct decision, although subsequent calculations by the NPL suggested that altitude could have been re-gained by leaving the engines at cruising speed.

The Accident Investigation Committee, under Major Cooper, determined that the nose down angle at impact was between 15° and 25°, although M. Rabouille¹⁸, a French poacher who witnessed the crash from about 300 yds, adjusted the Court's R.101 model to the impact angle as he recalled it, and the angle was determined to be 28 deg nose down.

The Court of Inquiry determined that R.101 was between 1,000 ft and 1,500 ft altitude, with 1,200 ft being most likely when the first dive occurred. As the crash site was 270 ft above sea level she would have lost 730-1,230 ft during the two dives. The calculations made by the NPL suggested the airship was 8° nose down at -730 ft, almost horizontal at -930 ft, and about 4° nose down at -1230 ft. Thus, the NPL impact angles are too small, despite the assumed assistance of a downward gust of wind and some tail lift generated by hydrogen thought to be trapped between the gas bags and the cover. Nevertheless, the Court of Inquiry, under Sir John Simon¹⁹, was satisfied and concluded that

“On inspection ... it will be apparent that the plotted course of the ship most closely agrees with the actual course of events”

The engineers and scientists at the NPL²⁰ were less easily pleased and thought that their calculation:

“... definitely indicates that some additional assumptions other than loss of gas should be sought in order to explain the final motion of the airship before she struck the ground”

In an earlier paper²¹ the author showed that this additional factor causing the second dive was the fracture of the elevator cable. It was always known that the elevator cable had snapped, Figure 13, but the Court of Inquiry had taken the view that it happened during the hydrogen fire that occurred after the impact. They believed this because the fracture was brittle rather than ductile, and Woodward²² had shown that the cable would break in a brittle

manner if exposed to a hydrogen flame. It could not, they thought, be the cause of the second dive.

However, the evidence from the Accident Report showed that the airship was compressed by



Figure 13 Major Cooper (?) holding the broken elevator cable near the 2:1 ratio auxiliary control drum at the tail end of the airship (frame 15)
National Archive, Kew.

81 ft during impact and the control room moved about 45 ft towards the elevator. This slack in the cable between the control room and the elevator allowed the elevator to fall from full up to full down (the position in which they were found) and this fall would unwind up to 13 ft of cable from the nearby auxiliary control pulley. This did not happen and the cable on the auxiliary control pulley was found to be complete. It follows, therefore, that the cable must have broken before impact and when the elevator was fully up. An alternative cause of hydrogen embrittlement was suggested.

It was shown that if the cable broke when the elevator reached the full up condition then the airship would crash at the desired nose down angle. In these calculations it had been assumed that gas bag 3 had burst to cause the first dive, but Davison²³ suggested that gas bags 1 and 2 were more likely to fail because the outer cover at the airship's nose had not been renewed with the rest of the cover immediately before the flight. It seems appropriate, therefore, to repeat the calculation but with gas bags 1 and 2 causing the first dive.

In determining the probable path of the R.101 during its final descent the estimates made by Squadron Leader Booth, Captain of the R.100, are used. He determined that the airship was 4.2 tons heavy before the accident and that there was 13.5 tons of fuel and water ballast which when dropped, would give a nose down moment of 115 ton ft. It is also assumed that initially the airship is in level flight and flying at cruising speed, hence for 4.2 tons of general heaviness the cruising speed is 90.1 ft/s, the elevator angle 6.3° down, and the pitch angle 1.35° up. The assumed elevator controls, computed flight path, forward velocity, and pitch angle, are shown in Figure 14.

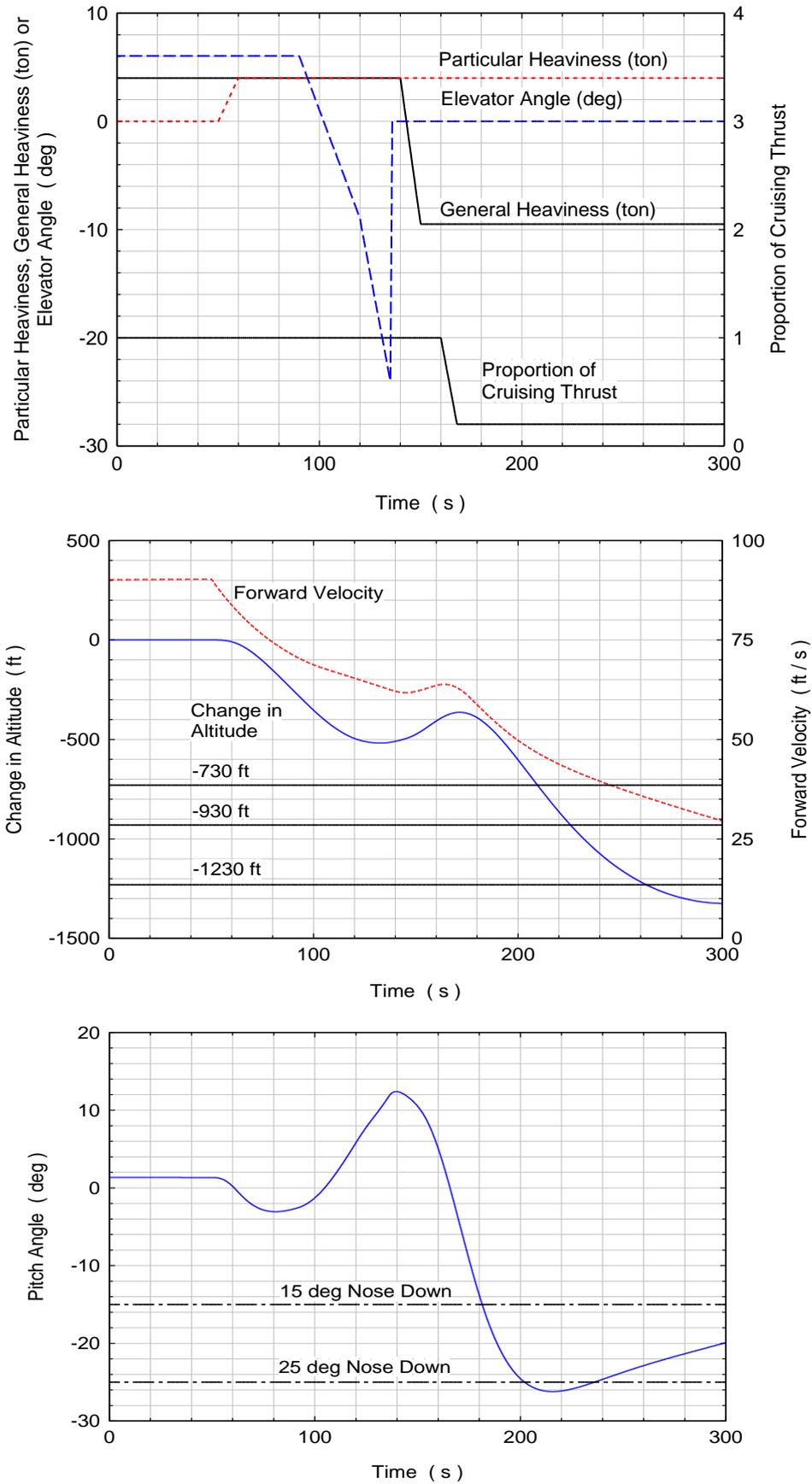


Figure 14 Top: General and particular heaviness, elevator angle, and proportion of propeller thrust; centre: forward velocity and change in altitude; bottom: pitch angle.

The first 50 s of Figure 14 illustrate the equilibrium flight. At 50 s the outer cover rips, increasing the drag by 0.0007 at 1ft/s, and gas bags 1 and 2 also rip and release 90 % of their contents over a period of 10 s, reducing the lift by 3.8 tons at a distance 294 ft forward of the centre of buoyancy. This causes the nose to droop and height is lost. At 90 s, when the ship has lost about 250 ft, the height coxswain reacts and starts to raise the elevator at 0.5 degree/s, but at 120 s, as the ship continues to lose height, he increases to the maximum rate of 1 degree/s until the elevator is fully up (-25°). At this point, 136 s, the airship has lost some 500 ft but appears to be pulling out of her dive.

Under the action of high aerodynamic forces and high dynamic forces, caused by the change in direction and speed of the airship, the elevator cable breaks. The crew realise that they have lost control and logically decide to make a soft landing by releasing all available ballast and cutting all five engines. This takes some time because the ballast is released, tank by tank, from the control room or locally by sending a man to do the job. The foremost ballast was not released before the crash. Also, the orders to cut the engines were given separately through speaking tubes, and the engineer on duty replied before he implemented the order. Four of the five engines were shut down before impact but a fifth was not because the engineer did not hear the warning bell in his noisy engine room.

Thus, it is assumed that the available 13.5 tons of fuel and oil ballast was dropped between 140 s and 150 s, and that four of the five engines were stopped between 160 s and 176 s. The airship continues to recover altitude between 130 s and 170 s, but after the engines were stopped she lost altitude and forward speed very quickly. The altitude of the crash site near Beauvais, is about 270 ft above sea level, and had the R.101 been flying at 1000 ft she would have lost 730 ft at impact. At this point the pitch angle was 26.0° nose down and the speed was 45 ft/s. Had she been flying at 1,200 ft, as assumed by the Court of Inquiry, the loss of altitude at impact would have been 930 ft and the pitch angle 25.8° . The cloud base was reported to be 1,500 ft and this is the upper altitude at which she would have flown, because the navigator, in those days, always needed to see the ground to determine the drift (at night or over the ocean flares were dropped). Thus, the maximum loss of altitude at impact is 1,230 ft, when the pitch angle is 22.6° down. As mentioned above, the Accident Investigation Committee, under Major Cooper, determined that the nose down angle at impact was between 15° and 25° , although M. Rabouille, the only witness of the impact, determined it to be 28° nose down, by using a model at the Court of Inquiry.

The forward speed was similar to the wind speed, so the impact velocity was low. This was confirmed by the survivors, who may have stumbled and fallen over but were not injured by the impact. The crew had achieved a soft landing. The loss of life happened in the hydrogen fire that occurred immediately after the crash.

Masefield and Simpson in 1996 used a more sophisticated computer simulation of the R.101's final flight path²⁴ and succeeded in bringing down the airship at the requisite 15° - 25° pitch angle, but only by assuming a somewhat long series of events, and assumed reactions to these events, and by a conjectured downward gust of wind leading to the first dive. A summary of their assumptions is shown in Table 2. These may be compared to the many fewer assumptions made in calculating Figure 14, which does not rely on Masefield and Simpson's downward

gust nor on the NPL's help of hydrogen gas trapped between gas bags and envelope. Instead, the hard evidence of a broken elevator cable is used.

Table 2 Comparison of Assumptions

Assumptions made by Masefield and Simpson.	Assumptions made for Figure 12
<p>Airship 2 tons heavy, speed c80 ft/s into a 40 ft/s headwind.</p> <p>Envelope tears causing increase in drag and nose up moment.</p> <p>To counteract nose up moment, down elevator applied at 0.3 deg/s for 30 s to reach 10 deg down</p> <p>To avoid exceeding pressure-point, elevator increased at 0.2 deg/s for 41 s to reach 2 deg up.</p> <p>Followed by a series of elevator movements to reach trim at setting of 6.6 deg down.</p> <p>2.75 ton water ballast released from Frames 6 and 11. (why?)</p> <p>Elevator wound up at 0.1 deg/s for 4s, then 0.5 deg/s for 5 s, then 0.75 deg/s for 22 s, and with two men at the wheel, at 1 deg/s for 10s.</p> <p>Down gust of wind (15 ft/s front, 7.5 ft/s down for 12 s) causes gasbags 1-2 and 3 to tear with loss of lift at 5.88 ton/min. Causes first dive.</p> <p>First dive overcome by fuel discharged from Frames 3 and 5.</p> <p>Ordered discharge of ballast from Frame 0 (1 ton) and a balancing discharge of water from Frames 12 and 14. Ballast not released from Frame 0, hence produced nose-up moment.</p> <p>Now only 488 ft above ground level and, with descent rate increasing even with elevators full up, stranding was inevitable.</p> <p>Remaining fuel jettisoned from Frames A and 10</p> <p>Engine Power reduced.</p> <p>Airship impacts at 18 deg nose down.</p>	<p>Airship 4.2 tons heavy (Booth), equilibrium flight assumed. Speed 90 ft/s, 44 ft/s headwind</p> <p>Envelope tears causing increase in drag and rupturing gasbag 1-2 which leaks 3.8 tons of gas in 10 s. Causes first dive.</p> <p>Elevator raised at 0.5 deg/s for x s and then at 1 deg/s until 25 deg up.</p> <p>Elevator cable breaks putting ship into second dive.</p> <p>All ballast dropped 13.5 ton (except from frame 0),</p> <p>Engine power reduced, to 20%.</p> <p>Airship impacts at 25 deg nose down.</p>

6. Conclusions

The NPL's mathematical model of the R.101 aerodynamics and their measurements of drag, lift, lifting moment and damping coefficients have been used to illustrate the airship leaving its mooring mast. She could reach cruising altitude and speed about ten minutes after leaving the mast, although passenger comfort may dictate a slower ascent. Changes in elevator at cruising speed and the reversal in elevator operation that occurs at low speeds have also been demonstrated. As with all airships, R.101 was in a condition of unstable equilibrium. Also determined are the effects of sudden changes in pitch, horizontal wind speed and thrust. Response is stable but there is a net gain or loss of altitude. The airship could recover

altitude and equilibrium after the loss of any single gas bag, except perhaps for gas bags 11, 12 and 13. The possible procedures for landing at her mooring mast from a height of 1,000 ft are illustrated and it seems that the descent needs to start about three miles from the mast. Finally, it is shown that the conditions necessary to crash the airship in the manner determined by the Court of Inquiry (leakage of hydrogen from gas bags 1 and 2, and fracture of the elevator cable after the first dive) caused the airship to impact at about 21° - 26° nose down, depending on the height at which she was initially flying. This is in close agreement with the 15° - 25° estimated by the Accident Investigators and the 28° recalled by the only close external witness (Rabouille).

Appendix A Equation of Motion of an Airship

The data required for the calculation of the airship's motion are all specified in D.H. Williams and A.R. Collar's report²⁵. Figure 1, above, illustrates the forces, moments, and geometry of an airship in their notation. This is not the modern convention but has been retained to avoid the possibility of transcription errors. The lifting force (F) is equal to the weight of the airship (mg) when it is trimmed and subsequently, during the flight, the airship may become heavy (w) due to the accumulation of rainwater on the cover or the loss of buoyancy; or may become light ($-w$) due to the consumption of fuel or the dropping of ballast. This is called the general heaviness. If a gas bag fails it reduces lift by P tons, at a distance k from the centre of gravity.

The equations of motion in the u , v , and q directions are also unusual in that they were written by the NPL, to save computational effort, using the ship axes as reference frame rather than the earth. Again, this has been retained. The equations are written as:

$$m_1 \dot{u} = T(u) + X(\theta, \eta)V^2 - (P + w)\sin \chi$$

$$\dot{x} = u$$

$$m_2 \dot{v} = (P + w)\cos \chi + Z(\theta, \eta)V^2 - Z_q Vq - muq$$

$$\dot{y} = v$$

$$B\dot{q} = M(\theta, \eta)V^2 + T(u)h - (Pk + M_r)\cos \chi - M_s \sin \chi - M_q Vq$$

$$\dot{\chi} = q$$

and

$$V = (u^2 + v^2)^{0.5} \quad \tan \theta = \left(\frac{v}{u} \right) \quad \chi = \alpha + \theta \quad F=mg \quad (\text{A.1})$$

$$u_x = u \cos \chi + v \sin \chi$$

$$v_y = u \sin \chi - v \cos \chi \quad (\text{A.2})$$

There are six simultaneous first-order differential equations to be integrated. The damping coefficients were measured by the NPL and may be approximated by:

$$\begin{aligned} Z_q &= 1450 + 1065|\theta| && \text{lb if } \theta \text{ is deg and} \\ M_q &= 4.2 + 3.6|\theta| && \text{lb ft if } \theta \text{ is deg} \end{aligned} \quad (\text{A.3})$$

The propeller thrust has been determined by Bairstow²⁶ and at cruising speed is given by:

$$T = 1.309 \times 10^{-4} u^2 - 0.05855u + 8.2388 \quad (\text{A.4})$$

Where thrust T is lb if u is ft/s.

For equilibrium

$$\dot{u} = \dot{v} = \dot{q} = q = 0 \quad (\text{A.5})$$

Thus, the equations of motion can be written as:

$$\frac{M(\theta, \eta) + hD(\theta, \eta)}{L(\theta, \eta)} = \frac{Pk + M_t}{P + w} - \left(h - \frac{M_s + wd}{P + w} \right) \tan \theta \quad (\text{A.6})$$

This is a useful relation between the external loads (P , w , M_s , M_t) and the elevator and pitch angles, and has the advantage of being independent of velocity. It is best to use a simple iterative method to determine θ , η , and V for equilibrium. Equilibrium values for $P = 0$ and $-15 < w < 15$ ton are shown in Figure 10 above.

The NPL took the masses of the airship to be the mass in slugs of air displaced by the ship ($7.25 \text{ ton s}^2/\text{ft}$) plus an allowance for virtual mass based on the results reported in R&M 613²⁷, namely 5% in the longitudinal direction and 100% in the transverse direction. The moment of inertia about the transverse axis was taken to be $5.26 \times 10^6 / 32.2 \text{ ton ft}^2$, to which an allowance of 75% was added for virtual mass effects. The virtual mass effects are similar to acceleration terms, so no increase is made on the right-hand side of the equations of motion. In practice, the solutions are remarkable insensitive to changes in mass or inertia.

The aerodynamic drag, lifting force and lifting moment were measured by the NPL and published in tabulated form by the Court of Inquiry report and in the subsequent R&M note²⁸. This report specified the lift, drag and moment at a speed of 1 ft/s and was not made non-dimensional as in modern practice, mainly to save their computational effort. This is retained for consistency. Figure A.1 shows a selection of data corresponding to wind direction (θ) (incidence), which is equal to pitch angle for horizontal flight, and the elevator angle (η). There is a slight lack of symmetry due to the protrusion of the five engine pods and the control room on the underside of the airship. To allow for increased drag when the outer cover is ripped the drag force is increased by 0.0007 ton at a velocity of 1 ft/s (about 6 ton at cruising speed).

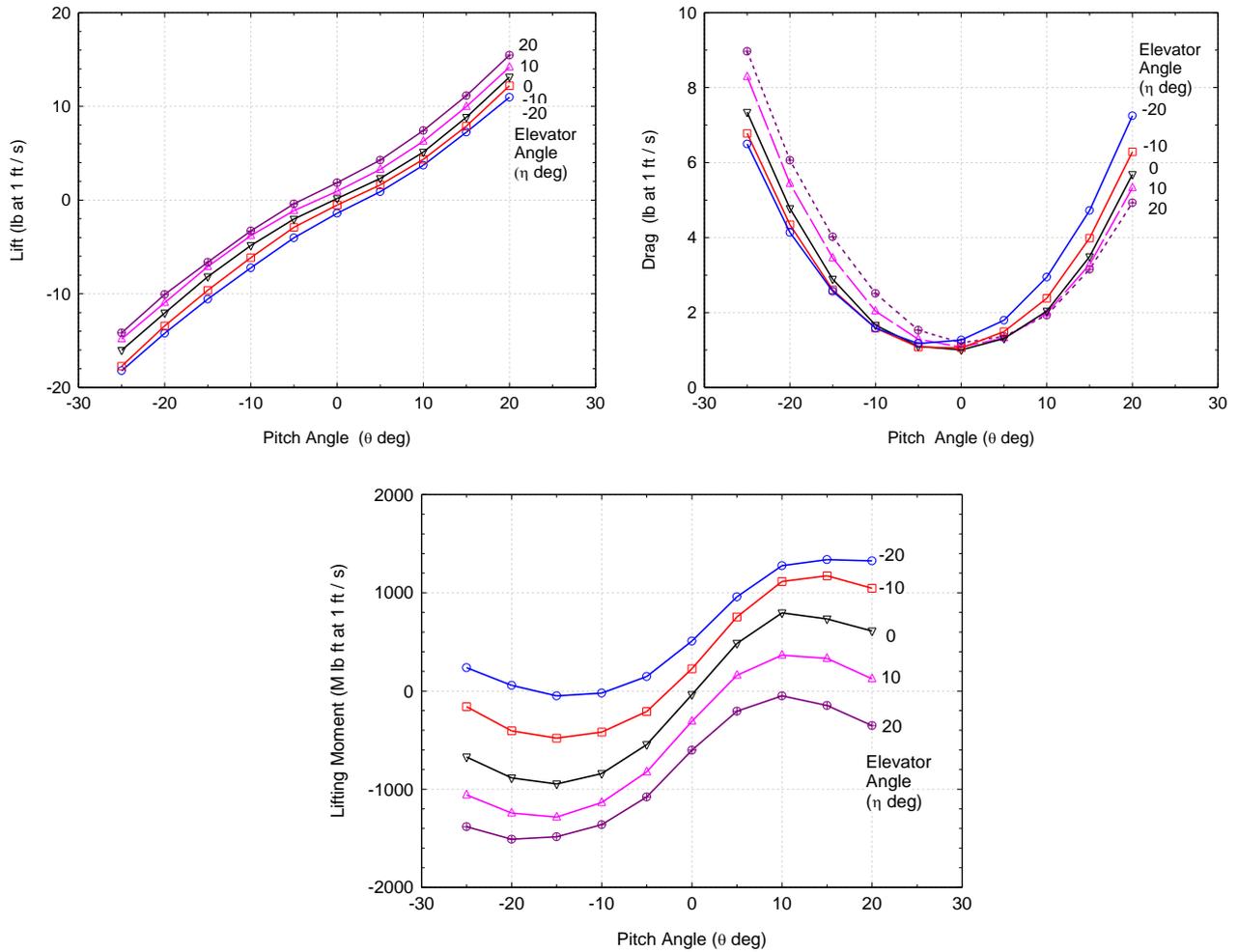


Figure A.1 Wind tunnel measurement of lift (top left), drag (top right) and lifting moment (bottom) measured by the NPL and scaled to full size for a wind speed of 1 ft/s. Lift and drag should be multiplied by -1 when used in Equations A1

The drag (D) and lift (L) shown in Figure A.1 were measured in the horizontal and vertical directions respectively, but the equations of motion are written in terms of the axial drag (X) and the trans-axial lift (Z). These quantities are related through the resultant force (R) as shown in Figure A.2.

$$\begin{aligned}
 R &= (D^2 + L^2)^{0.5} & \beta &= a \tan(L/D) \\
 X &= R \cos(\beta + \chi) & Z &= R \sin(\beta + \chi)
 \end{aligned}
 \tag{A.7}$$

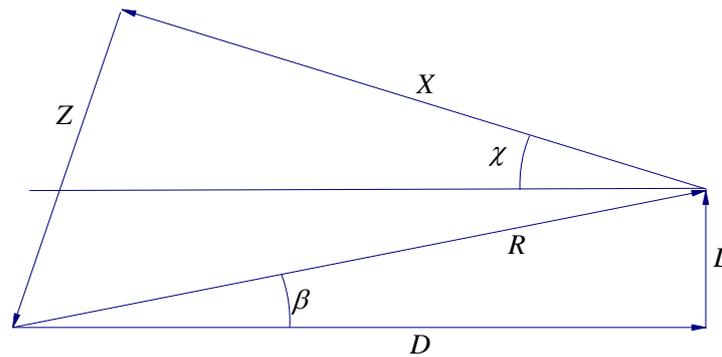


Figure A.2 Relation between drag (D) and lift (L) and the axial drag (X) and the trans-axial lift (Z)

Notation

Note that mass units are slugs (lbs^2/ft) and tons are converted using 2240 lb/ton.

B	effective inertia of airship, $2.86 \times 2240 \times 105 \text{ lbs}^2\text{ft}$
D	aerodynamic drag at 1 ft/s, lb
h	Distance between propeller thrust and centre of buoyancy, 60 ft
k	Distance between force P and centre of buoyancy, ft
L	aerodynamic lift at 1 ft/s, lb
m	mass of airship (mass of air displaced), $7.25 \times 2240 \text{ lbs}^2/\text{ft}$
m_1	longitudinal virtual mass, $7.5 \times 2240 \text{ lbs}^2/\text{ft}$
m_2	transverse virtual mass $13.5 \times 2240 \text{ lbs}^2/\text{ft}$
M	lifting moment, lb ft
M_s	static moment, $4300 \times 2240 \text{ lb ft}$
M_t	trimming moment, 0 lb ft
M_q	moment due to rotation and translation at 1 rad/s, lb ft
P	heaviness due to forward gas loss (at distance k), lb
\dot{q}	rotation acceleration, rad/s^2
T	propeller thrust, lb
\ddot{u}	acceleration in direction x , ft/s^2
u_x	horizontal velocity, ft/s
\ddot{v}	acceleration in direction y , ft/s^2
v_y	vertical velocity, ft/s

V	resultant velocity, ft/s
w	general heaviness of airship excluding P acting through centre of gravity, lb
x	distance along path, ft
\dot{x}	velocity along path, ft/s
X	Axial drag at 1 ft/s, lb
y	distance normal to path, ft
\dot{y}	velocity normal to path, ft/s
Y	altitude, ft
\dot{Y}	vertical velocity, ft/s
Z	trans-axial lift at 1ft/s, lb
Z_q	force due to rotation and translation at 1 rad/s, ft lb
α	direction of motion of centre of gravity relative to horizontal, degree or radian
θ	direction of motion of centre of gravity relative to airship centre line, degree or radian
χ	direction of airship centre line relative to horizontal, $\chi = \alpha + \theta$, degree or radian

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