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THE R-38 CATASTROPHE AND THE MECHANICS OF RIGID AIRSHIP CONSTRUCTION

(German translation of Spanish article published in "Memorial de Ingenieros," by Emilio Herrera, Chief of Engineers, Madrid.)

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THE R-38 CATASTROPHE AND THE MECHANICS OF RIGID AIRSHIP CONSTRUCTION.*

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The dreadful disaster which overtook the English rigid airship R-38, on August 24, 1921, and in which 44 men perished, was a terrible shock to the whole aeronautic world, since (in view of the successful operation of regular air traffic lines by the Germans, both before and after the war, with Zeppelin airships which covered over 300,000 km., without the least injury to any passenger), it was confidently assumed that airship construction had already been perfected to such a degree as to solve the problem of long distance air traffic with the essential factor of safety, which could not be attained by airplanes for a long time to come.

Of course, thorough investigations were undertaken, in order to determine the causes of the catastrophe, as to whether they were inherent in the system itself and therefore impossible to avoid in this kind of airship, or whether, on the contrary, the accident resulted from errors in construction, unforeseen occurrences, or faulty operation in this particular instance, which would in no way affect the use of rigid airships.

The airship R-38, built in the workshops of the Short Brothers, in Bedford, and finished by the British Admiralty, was de-

* From "Luftfahrt," April, 1922.

signed for the North American Navy as the ZR II and was destroyed in the attempt to fulfill the very hard acceptance conditions. Its main dimensions were: length 212 m.; diameter 26 m.; gas capacity, 77,000 cu.m.; engine power, 2100 HP (6 engines of 350 HP each); carrying capacity, 50 tons; speed, 120 km/h.

The rigid frame consisted of duralumin girders, similar to the ones used in Zeppelin airships, but it was built under special conditions, which must be taken into account in endeavoring to determine the causes of the disaster.

In the first place, it was the largest airship ever built, its gas capacity being 8500 cu.m. larger than that of the largest Zeppelin, and its construction presented more difficult technical problems than those already solved for the Zeppelins.

Its carrying capacity was about 60% of its total lift, a figure which likewise exceeded that attained by previous airships and which could only be reached by reducing the weight of the frame at the expense of its strength. The above ratio of carrying capacity to total lift (maximum lift of an airship, without the dynamic power obtained in oblique ascent) enables the determination of the static altitude in the following manner.

When an airship ascends without load, it can rise to a certain height, where the air density is only 60% of its value at sea-level, which according to the formula

$$Z = 18400 \log \frac{\delta_0}{\delta}$$

(in which Z is the attainable altitude, δ_o the air density at sea-level, and δ the air density at the height limit), corresponds to an altitude of 7360 m., which is necessary in order to be beyond the reach of anti-aircraft guns.

Such a static altitude had hitherto not been attained by any airship, since it was considered unsafe to make the requisite reduction in the weight of the frame.

But, in order to fulfill these exceptional conditions, this airship showed various original and daring innovations, which were in no way sanctioned by experience.

The radial bracing of the main rings or transverse frames, by which the interior of the airship was divided into separate gas cells, was replaced by tangential bracing and the number of cells or compartments was reduced to 14, instead of 18, as possessed by the largest Zeppelins. This gave increased lift, but the free portions of the longitudinal girders between the rings (subjected to pressure and bending stresses) were increased to 15 m., instead of 11 m., as on all Zeppelins, excepting the ones with longitudinal stays, which were lacking, however, on the R-38. Thus the strength of these girders was greatly reduced.

Moreover, it must be borne in mind that the builders of this airship of such unusual characteristics, had previously built no metal airship, but that their experience in this field of such difficult and delicate work was limited to the rigid wooden airships R-31 and R-32 which came from their shops several years ago.

During the building, various longitudinal girders broke under the weight of the workmen. During inflation, other girders broke and the first trial trip showed that the entire frame was too weak, necessitating various repairs and reinforcements.

The airship had tanks for 40,000 liters of gasoline and could fly 9,600 km. at full speed, or 14,500 km. at cruising speed. Its radio station had a range of 2,400 km., and was fully equipped for radiotelephony and for obtaining its bearings by radio.

The acceptance conditions consisted in the demonstration of the above-mentioned flight characteristics. On the fourth and last trip of this airship, which was begun at 7:10 a.m., August 23, from the Howden airdrome, the speed and maneuverability tests were to be made. The latter tests (severest of all) consisted in flying in sharp zigzags for 20 minutes, in order to test the strength of the frame and the working of the rudder.

The airship remained the whole day and night of the 23d, in the air and when, after successfully completing its speed tests, it was above Hull at 6 o'clock on the morning of August 24, the rudder tests were begun with three successive turns, with the rudder hard over. During the third turn the frame of the airship gave way near its center of gravity from the lateral bending stresses, whereupon there was immediately a series of explosions, followed by fire and the plunge of the giant airship into the Humber, not far from the harbor of Hull.

The exceedingly violent explosions which broke the window panes of the city of Hull, showed that they took place after injuries to the gas bags and the formation of an explosive mixture of air and hydrogen, which was probably ignited by the exhaust gases from the engines.

In order to facilitate the explanation of how the fatal break must have occurred, we will give briefly a general idea of what may be termed the mechanics of rigid airships.

Generally the frame of a rigid airship (Fig. 1) consists of a series of rings (ccc) or regular polygons, between which are the gas bags and which are connected by longitudinal girders (*ll*) extending from the nose to the tail, where the rudders and elevators are attached.

The frame thus formed, may be regarded as a rigid girder subjected to a number of forces which, according to their nature, may be classified as follows: weight or loads (force of gravity); lifting forces (aero-static); accelerations (dynamic). These forces must be in equilibrium in the three most important cases during flight: (1) When the airship is floating (aerostatic problem); (2) When flying without acceleration (aerodynamic problem); (3) When under the influence of any accelerating force (dynamic problem). We will briefly consider each of these cases.

1. Aerostatic Problem.

When an airship is at rest with respect to the surrounding air, it is subjected to the force of gravity resulting from the weights of the various parts and the loads carried, and to the lift exerted by the gas bags. Both forces change during flight, the former being diminished by the fuel consumption and release of ballast, though it may be increased by rain or snow. The lifting force changes with the temperature of the gases and of the air and with changes in altitude and usually decreases constantly from osmose, permeability of the gas bags, leaky valves, etc.

Since the direction of all these forces is vertical, there is equilibrium when the sum of the upward forces equals the sum of the downward forces and their respective resultants pass through one and the same point.

If the length of the airship is represented by the line AB (Fig. 2) and there are drawn at right angles to this line ordinates representing the cross-sectional areas of the gas space, we then have a diagram analogous to the displacement curve in shipbuilding, representing the distribution of the lifting forces along the longitudinal axis of the airship. This curve can change with the quantity and buoyancy of the gas in the bags, but will always keep inside of a curve (plain line), which represents the lifting force when the airship is completely filled with pure hydrogen at sea-level with the highest possible temperature of the hydrogen gas and the lowest possible temperature of the surrounding atmosphere.

As regards the loads or weights carried, a distinction is made between those which remain constant during flight (weight of airship itself and of the crew) and the changeable weights (fuel, food, ballast).

If we take, perpendicular to the line AB, ordinates representing the constant weights, we have the load curve corresponding to the last part of the flight, after all the fuel, food and ballast have been used up. The resultant of all these minimum weights must be offset by the lifting force of the remaining gas. This is the case when the area, between the dash curve of the minimum lift (whose ordinates must be proportional to those of the maximum lift) and the longitudinal axis AB equals the dark area bounded by the curve of constant weight and when, at the same time the centers of gravity of the two areas have the same abscissas. In designing an airship, the constant weights must accordingly be distributed so as to fulfill this condition.

The variable loads (hatched area) must be so distributed that their variations will not displace the center of gravity, or so that their center of gravity will always have the same abscissa AG. Thus the magnitude and distribution of the maximum loads can be established so that the area included in its curve will equal that of the maximum lift.

The distribution of these loads may be accomplished in various ways. We must choose the method which will exert the smallest bending stresses on the members of the frame. In this connection we see that, in every cross-section of the airship, there is exerted a resultant force which equals the difference between the corresponding lift and weight. And if, for each point of the axis we introduce a new ordinate which represents the moment of the forces between it and the one end of the airship, we can then draw the curve of the bending moment (dot line in Fig. 2), in which we consider as positive bending moments those which tend to bend the ends of the airship upward and as negative those which tend to bend them downward. If we draw the corresponding curves for various load distributions, we can find empirically the curve which gives the minimum bending moment. We must bear in mind, however, that some solutions are impracticable, namely, when they indicate an extraordinary accumulation of weights in any given cross-section. This would produce a relatively large shearing force which would necessitate strengthening the corresponding section of the frame.

The loads are generally supported by the rings, partly direct and partly by a girder inside the hull, which also serves as a connecting corridor. The lifting forces of the gas bags are transferred by means of a net to the longitudinal girders of the frame and to the corridor girder.

2. Aerodynamic Problem.

When the airship is flying, the driving force P (Fig. 3), is transferred by the propellers to the cars or gondolas which, being rigidly attached to the frame of the airship, in turn support the motion of the airship by overcoming the air resistance R, whereby the longitudinal girders in front of the engine cars are subjected to pressure. Since the air resistance acts chiefly in the direction of the axis of the hull and the engine cars are located outside of and below the hull (for aerostatic stability), there is generated a moment which tends to make the airship nose up. This moment must be neutralized by an equal and opposite moment F-F produced by the elevators. The latter moment takes the form of a bending moment (hatched area) to which all cross-sections behind the first engine car are subjected. For every cross-section, this moment is equal to the moment of the forces F-F, which are behind the cross-section under consideration, minus the moment of the propeller forces for this portion of the air ship.

In each cross-section, this bending moment is exerted on all longitudinal girders, the stresses being proportional to the distance from the neutral zone. Hence the forces produced in each individual girder offset a portion of the total bending moment and indeed proportional to the square of their distance from the plane of the neutral axis.

When an airship, through uneven distribution of its load, flies on an inclined keel, the air, striking obliquely against the hull and especially against the horizontal tail planes, exerts a force equal and opposite to those of all the balancing static forces, which likewise give rise to corresponding bending moments in the different cross-sections. These bending moments must be computed in the same manner as those produced by static forces, while also taking into consideration the lateral components of the air pressure in each cross-section.

3. Dynamic problem.

The most important case of the dynamic problem occurs when, with the airship going at full speed, the elevators and rudders are suddenly displaced to their full extent. At this instant (Fig. 4) there is produced against the rudder an air pressure, whose lateral component tends to turn the airship about its center of rotation O. This lies in front of the center of gravity g at a distance equal to the moment of inertia of the airship divided by the product of its mass times the distance between the center of gravity g and the center of application of the rudder force. In other words, the product of the distance of g from O and from the rudder surfaces is equal to the square of the radius of inertia of the airship.

The angular acceleration given the airship is equal to the moment of the rudder force, with reference to the center of gravity, divided by the moment of inertia of the airship and this angular acceleration produces rectilinear accelerations in the different cross-sections, according to their distance from O. Thus there are produced in every cross-section, through the linear acceleration, inertia forces equal to the product of the mass times the acceleration. These forces (shown in Fig. 4) produce bending moments (dot curve), whose maximum occurs a little behind the center of gravity.

Application to the R-38.

With 77,000 cu.m. gas capacity and 1.1 kg. per cu.m. lifting force of commercial hydrogen, we can assume the maximum aerostatic force of the airship to have been about 85 metric tons and the minimum 35 tons (weight of airship without variable load). The variable load would therefore be 50 tons.

The aerodynamic forces of the airship, in horizontal flight under full engine power, may be computed in the following manner. With an engine power of 2100 HP, or 157,500 kgm/sec., and a speed of 120 km/h, or 33.3 m/sec., the pulling force, if it could be completely transferred, would be 157,500 divided by 33.3, or 4725 kg., and if we assume a propeller efficiency of 70% (the usual value), we would have 3300 kg. pulling force, which also equals the air resistance to be overcome by the airship. The nose is therefore subjected to this pressure which, in this particular instance, is divided between 20 girders, so that each girder is subjected to a pressure of 165 kg.

The distance of the middle line of the air resistance from the plane of the propeller axes was about 15 meters. The moment tending to make the airship nose up (dynamic tail-heaviness) was accordingly 3300 x 15, or 49,500 kgm., which had to be offset by a force of 49500/120, or 413 kg., exerted by the elevators, if we assume that the elevator surfaces were about 120 m. from the center of gravity. Applied at a distance of 80 m., i.e., in the vicinity of the rear engine cars, this force would have exerted a bending moment of 413 x 80, or 33,040 kgm., which the 20 girders had to withstand, the upper ones in pressure and the lower ones in tension

If the radius of the airship is taken as one, then two of the girders are in the neutral plane, four at 0.31, four at 0.59, four at 0.81, four at 0.95, and two at 1.00 distance from the same plane. The force generated in each girder would be proportional to the square of its distance, i.e., to 0.10, 0.35, 0.65, 0.90, or 1.00. These numbers multiplied by the corresponding numbers of girders and added together, give 10, from which it may be deduced that in the most stressed girders, i.e., in those farthest from the neutral plane, a moment of 33040/10, or 3304 kgm., is produced and that, with a lever arm of 13 m. (radius of airship), the force to be withstood by each girder would be 3304/13, or 253 kg.

The dynamic forces are more difficult to compute because we need to know the moment of inertia of the airship, for which we have no satisfactory data. We can, however, make an approximate computation, by taking as its basis a homogeneous girder of the same length and mass as the airship.

The total mass M of the airship is 85,000 kg., not including the mass of the 77,000 cu.m. of hydrogen (about 15,000 kg.), or altogether 100,000 kg. With an over-all length of the airship of 212 m., we will take 210 m. as the length of a girder, disregarding the tip of the tail.

The total area of the vertical stabilizers and rudders was about 100 sq.m., which was about the same as the total area of the horizontal stabilizers and elevators and since, with the rudders hard over, an aerodynamic coefficient K_y of 0.04 can be obtained, the transverse force at the tail could be about $F = K_y S V^2 = 0.04 \times 100 \times 33.3^2 = 4.5$ metric tons.

A 100-ton girder 210 meters long, would have a moment of inertia $J = \frac{100000}{g} \frac{210^2}{12} = 384,200,000$ kgm. sec.², and its center of rotation, with the application of a transverse force at one end, would lie $\frac{J}{105\ M} = \frac{210}{6} = 35$ meters in front of the center of gravity. In this case the angular acceleration A would be $\frac{4500}{284200000} = \frac{1}{63155}$ per second.

The force of inertia, produced in every cross-section at a distance of x from the center of rotation, will have a value of $M \times A \times x$, in which M represents the mass of the cross-section under consideration. By representing these forces graphically (Fig. 5), we obtain the similar triangles S and s, the algebraic sum of whose moments, with reference to a given cross-section, give the bending moment in the same cross-section. This sum of the moments may be expressed:

$$S\left(\frac{2}{3}\,70 + x\right) - s\,\frac{1}{3}\,x$$

and if we make $\frac{S}{s} = \frac{70^2}{x^2}$, we obtain for the bending moment

$$\frac{S}{3}\left(140 + 3x - \frac{x^3}{70^2}\right)$$

Dynamic equilibrium, however, requires $F = S\,\frac{140^2}{70^2} - S = 3\,S$ from which we obtain, as the bending moment for each cross-section

$$\frac{F}{9}\left(140 + 3x - \frac{x^3}{70^2}\right)$$

The maximum bending moment will occur in the cross-section corresponding to the value of x where its differential quotient $\left(3 - \frac{3x^2}{70^2}\right)$ vanishes, i.e., for $x = 70$ M. This cross-section is 35 meters behind the center of gravity and its bending moment is

$$\frac{F}{9}\,(140 + 3 \times 70 - 70) = \frac{280}{9}\,F = 140000 \text{ kgm.}$$

The girders farthest from the neutral plane must therefore be able to withstand a force of $\frac{140000}{10 \quad 13} = 1077$ kg.

If this force is added to the above-mentioned aerodynamic stresses we find that the girders would each be subjected to a total stress of about 1250 kg. at the center of gravity of the airship, where the break actually occurred.

We see therefore that the dynamic effect of a violent rudder displacement, which was easily produced on this airship with its balanced rudders, could be more than four times as large as the combined static and aerodynamic loads during ordinary flight. It is not strange, therefore, that a rigid airship, whose frame had already been strained by the two latter forces and was then within a few minutes, while still under maximum engine power, put to the fearful test of having its rudder thrown hard over, should break entirely in two.

Translated from the German by the National Advisory Committee for Aeronautics.

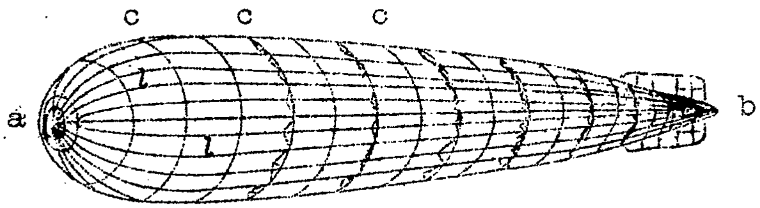

Fig. 1. Frame of hull.

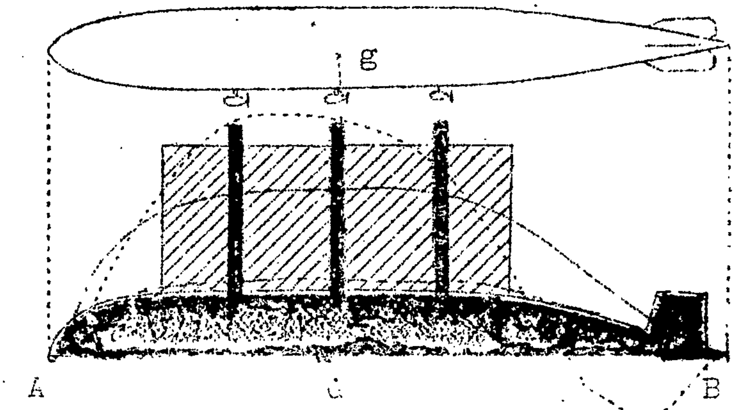

Fig. 2. Distribution of static forces.

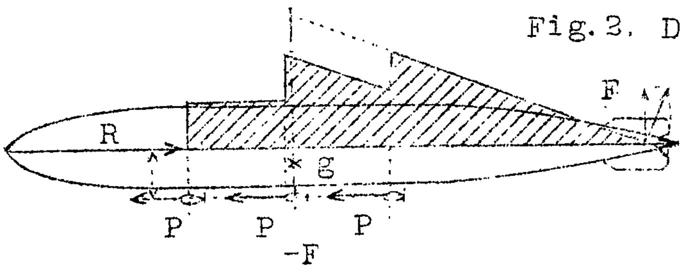

Fig. 3. Aerodynamic forces and moments.

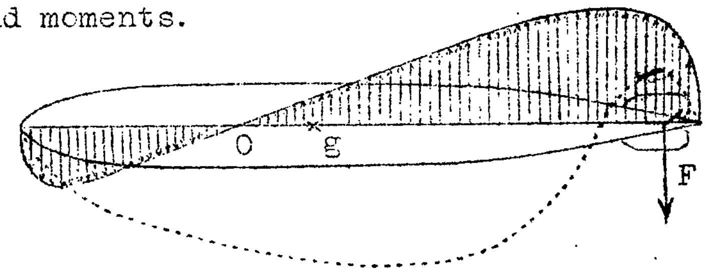

Fig. 4. Forces and moments produced by throwing rudder hard over.

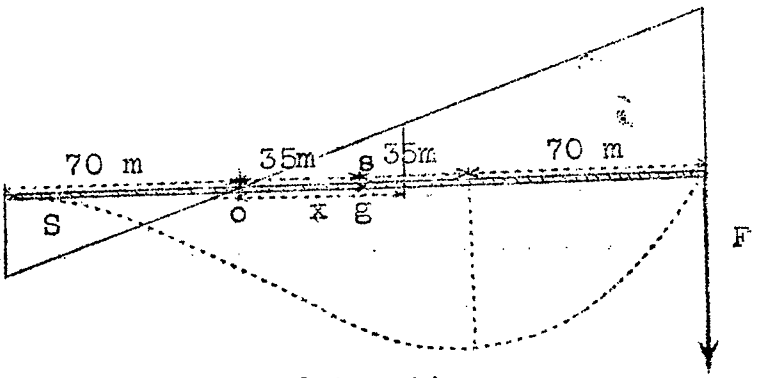

Fig. 5. Forces of inertia.