CONSEQUENCES OF INCREASING WATER BALLAST

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1. INTRODUCTION

To obtain the best shape of the speed polar sailplane designers pay the special attention to the high speed portion of the curve responsible for the competition performances.

To move the speed polar towards the high speed region water ballast is used. Therefore, recent sailplanes are equipped with tanks in the wings enabling one to carry more and more water. The water ballast mass on the modern 15-m span gliders (standard and flapped class) reaches a value equal to the mass of the empty glider. Such a great mass increment improves, of course, the high speed performance but requires some penal costs to be paid, mainly in lowered controlability and increased loadings.

The main design parameters responsible for these characteristics are the all-up mass and inertia moments of the ballasted ship.

To illustrate the influence of increasing water ballast on the controlability and structural loads the particular values have been presented for the Polish competition Standard Class sailplane SZD-55 having the following design data :

me= 215 [kg] - empty sailplane mass, with basic competition equipment included

mb	- water ballast mass (maximum 195 [kg])
m = 500 [kg]	- design all-up mass
b = 15 [m]	- wing span
NN-27	- wing profile
$CL_{max} = 1.484$	- maximum lift coefficient
$S = 9.6$ [m²]	- wing area
$l_o = 0.6874$ [m]	- mean standard chord of wing

The analysis has been carried out for various water ballast masses ranging from zero to the maximum value of 195 [kg].

As the variable the ratio :

$$\o = \frac{m_b}{m_e}$$

has been introduced.

For the SZD-55 sailplane the ratio ø varies between 0 to 0.907. The analyzed range of all-up masses was from:

$$m = m_{empty} + m_{pilot} = 215 + 110 = 325 \text{ [kg]}$$

to the maximum allowed all-up mass (water tanks full) of 500 [kg].

2. CONTROLABILITY

The variations in the amount of water ballast influences mainly the rolling and yawing controlability, while pitching affected is not significant. The deciding factor is the water tank span which moves towards the wing tip when the water amount increases.

As a consequence the variation of the inertia moments with respect to the longitudinal (J_x) and vertical (J_z) axes appears.

2.1. Rolling controlability

To investigate the influence of the water ballast amount on the rolling ability of the sailplane the parameter "k_x" has been introduced :

$$k_x = \frac{S_A \bullet y_A}{J_x}$$

where :

- S_A - aileron area (see Figure l)
- y_A - distance of the aileron midspan point with respect to the glider plane of symmetry (see Figure l)
- J_x - moment of inertia with respect to the longitudinal axis

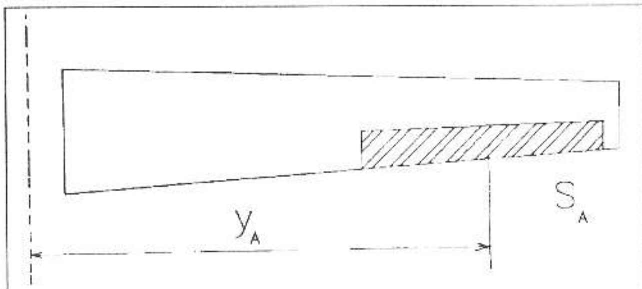

FIGURE 1.

The product $S_A \bullet y_A$ represents the geometrical characteristics of the rolling moment and J_x decides on the glider response.

The relationship of: $k_x = f(\o)$ for SZD-55 sailplane is shown on Figure 3. For the maximum mass ratio of ø = 0.907 the decrement of k_x ranges about 28 per cent. For comparison the values of k_x for several Polish glider types are listed in Table 1.

The value of $k_x = 0.86 \bullet 10^3$ for SZD-55 with no ballast decreases to $k_x = 0.62 \bullet 10^3$ for the full ballast. This last value corresponds to k_x for SZD-42-2 JANTAR 2B sailplane of the Open Class. Ships of this class are known as requiring the special pilot's attention during the take-off especially in the very beginning on the ground run.

2.2. Yawing controlability

For the yawing controlability the parameter "k_z" has been introduced

$$k_z = \frac{S_V \bullet L_V}{J_z}$$

where :

- S_v - fin and rudder area (see Figure 2)
- L_v - vertical tail force arm with respect to the glider c.g. (see Figure 2)
- J_z - moment of inertia in respect to the vertical axis

The product: $S_v \bullet L_v$ represents the geometrical characteristics of the yawing moment and J_z decides on the glider response.

The values of $k_z = f(\o)$ for SZD-55sailplane are plotted on Figure 3. The decrement of k for increasing amount of water is slightly lower (proportionally) than that of k_x. The statistics for k value are listed in Table I.

3. GUST CONDITIONS

According to the requirements (OSTIVAS, JAR-22) the gust condition airspeed is established for the maximum all-up mass of the glider that means for the full

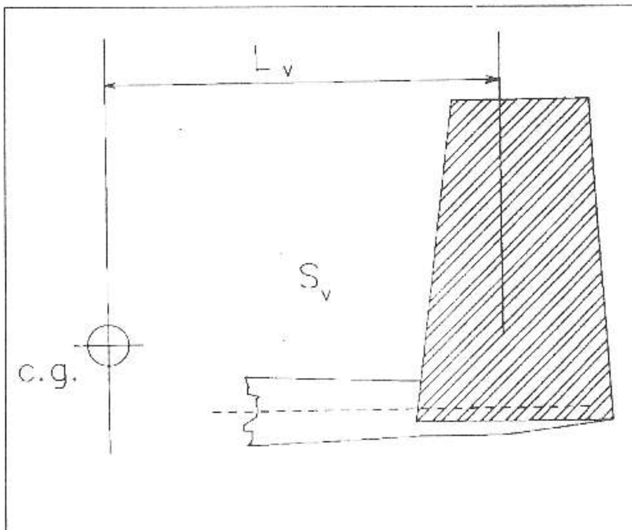

FIGURE 2.

TABLE 1. Controlability factors k_x and k_z

Glider	structure	k_x	k_z
STANDARD CLASS ballastless			
SZD-30 Pirat	wooden	1.100	1.950
SZD-32 Foka 5	wooden	1.410	1.400
SZD-36A Cobra	wooden	0.980	1.450
SZD-43 Orion	wooden	0.892	1.236
SZD-51-1 Junior	compos.	0.863	1.559
STANDARD CLASS with the full water ballast			
SZD-41A Jantar Standard 1	compos.	0.820	1.584
SZD-48-3 Jantar Standard 3	compos.	0.780	1.005
OPEN CLASS ballastless			
SZS-29 Zefir 3	wooden	1.080	1.020
OPEN CLASS with the full water ballast			
SZD 38A Jantar 1	compos.	0.710	0.861
SZD-42 Jantar 2	compos.	0.630	0.680
SZD-42-2 Jantar 2B	compos.	0.640	0.610
TWO-SEATERS ballastless			
SZD-35 Bekas	wooden	1.236	2.165
SZD-50-3 Puchacz	compos.	1.000	2.159

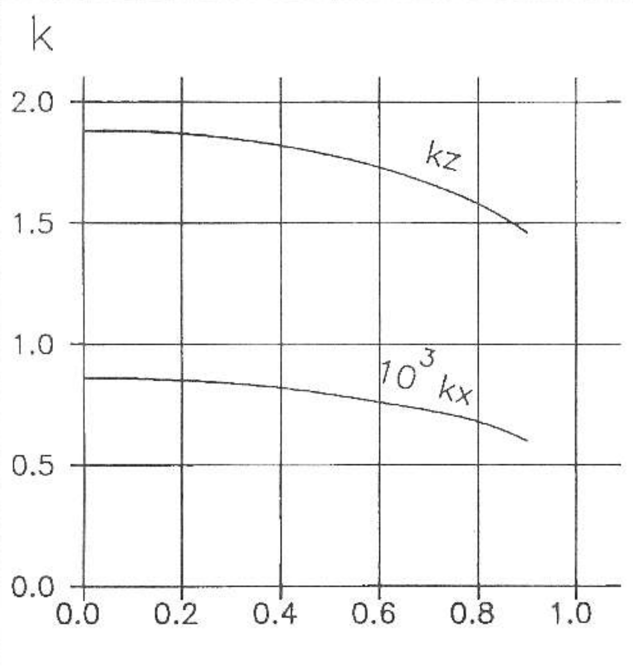

FIGURE 3.

water ballast. This airspeed is the same for both configurations : with and without water ballast.

The authors of the airworthiness requirements assumed that for operational reasons it is recommended to give the pilot only one value of V_{RA} for the most severe mass configuration. This, however, results in higher structural loads for the ballastless configuration.

The analysis of gust conditions concerns the gust intensity of $U = \pm 15$ [m/s] at V_{RA} and $U = \pm 7.5$ [m/s] at V_D.

3.1. Gusts of U = ± 15 [m/s]

Following the JAR-22.335(c) requirement the V_{RA} airspeed is :

$$V_{RA} \geq V_A$$

where :

$$V_A = V_s \bullet \sqrt{n_1}$$

V_S - stalling speed for the maximum design mass (i.e. with full water ballast)

n_1 - maximum positive maneuvering load factor

The situation for the gust of $U = +15$ [m/s] on the load envelope is shown on Figure 4. For the ballastless version at the airspeed $V_I = V_{RA}$ the load factor is n_1. For the ballasted version $V_{RA} = V_{II}$ and the same value concerns now the ballastless configuration resulting the load factor increasing up to n_{11} value. The increment $\Delta n = n_{II} - n_I$ depends on the water ballast amount which increases V_{RA}. The variation of V_{RA} versus the mass ratio ø is shown on Figure 5.

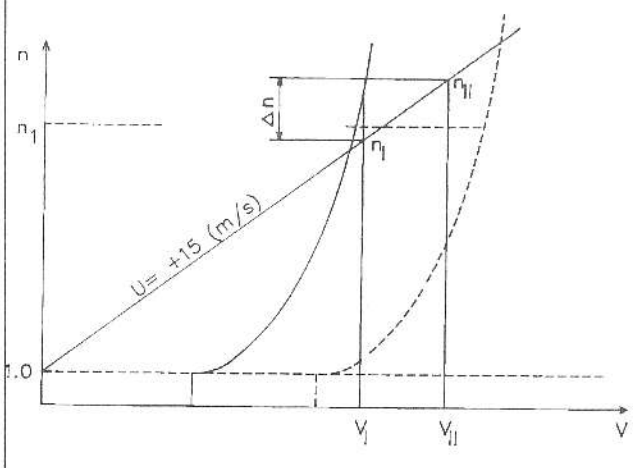

FIGURE 4.

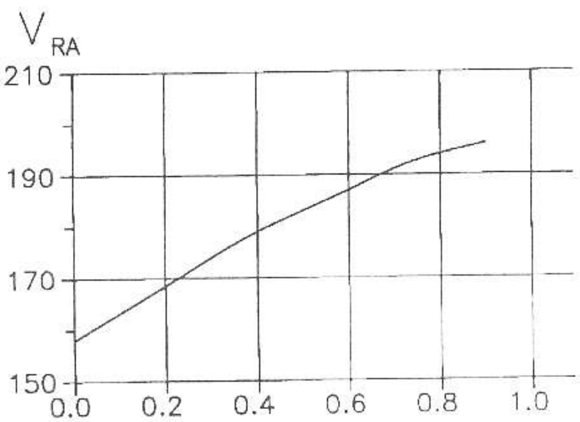

FIGURE 5.

The gust load factor is defined by the formula:

$$n = \frac{1}{2} \bullet \rho_o \bullet k \bullet a \bullet U \bullet \frac{S}{m \bullet g} \bullet V_{RA}$$

where :

- ρ_o - air density at the sea level
- a - slope of the wing lift curve
- U = ±15 [m/s] - gust intensity
- S - wing area
- m - all-up mass of the glider
- g - gravity acceleration

$$k = \frac{0.88 \bullet \mu}{5.3 + \mu}$$ gust alleviation factor

$$\mu = \frac{2 \bullet m}{S \bullet l_m \bullet a}$$ mass parameter

l_m - wing mean standard chord

For the ballastless configuration the gust alleviation factor "k" has the value for ø = 0 while for the ballasted configuration it is k = f(ø). Both k and V_{RA} values influence the load factor.

The relationship of load factor versus mass ratio for ballasted and ballastless configurations for SZD-55 sailplane is plotted on Figure 6 where the particular curves denote:

- a - gust of +15 [m/s] in ballastless configuration
- b - gust of +15 [m/s] in ballasted configuration
- c - gust of -15 [m/s] in ballastless configuration
- d - gust of -15 [m/s] in ballasted configuration

The solid lines concern the positive and dotted the negative load factor values.

The shape of curves "b" and "d" ((ballasted configuration) shows the variable gradient for the higher values of mass ratio ø since the all-up mass of the sailplane is

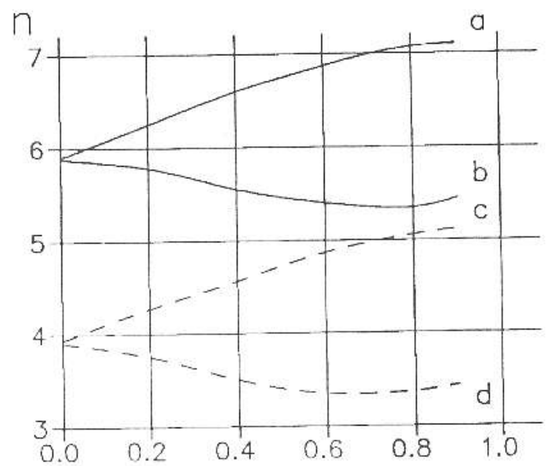

FIGURE 6.

limited and influences the cockpit loading possibilities.

3.2. Gusts of U = ± 7.5 [m/s]

The design maximum speed accordingto JAR-22.335(f) is:

$$V_D = 18 \sqrt[3]{\frac{m \bullet g}{S \bullet C_{Dmin}}} \quad \text{[km/h]}$$

where: $C_{D\,min}$ - minimum drag coefficient of the glider.

The variation of V_D versus mass ratio ø for SZD-55 sailplane is shown on Figure 7.

The load factors calculated in the same way as in paragraph 3.1. have been plotted on Figure 8 as a function of mass ratio ø where the particular curves denote :

- e - gust of +7.5 [m/s] in ballastless configuration
- f - gust of +7.5 [m/s] in ballasted configuration
- g - gust of -7.5 [m/s] in ballastless configuration

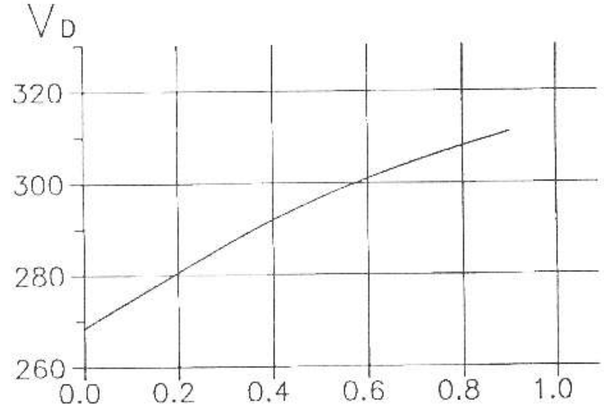

FIGURE 7.

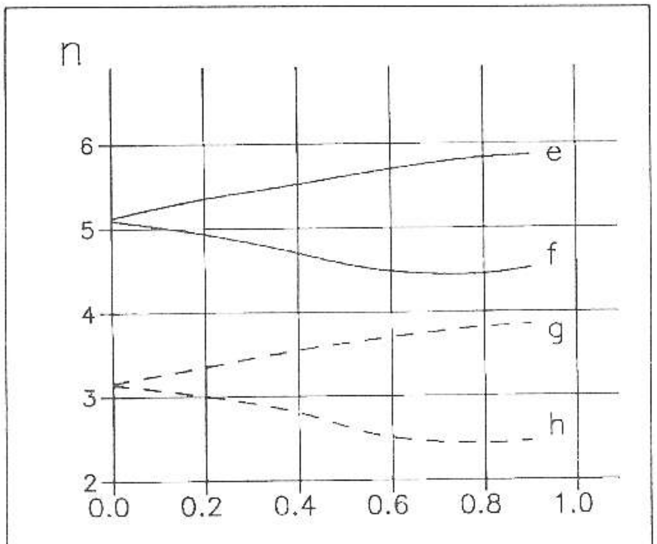

FIGURE 8.

h - gust of -7.5 [m/s] in ballasted configuration
The solid lines concern the positive and dotted the negative load factor values.

4. LOADS ON GLIDER COMPONENTS

4.1 Wing

The wing in flight is loaded by the aerodynamic and mass forces (Figure 9). The shape of the aerodynamic forces distribution depends on the circulation intensity along the span. The mass forces are distributed proportional to the mass of wing structure (and water ballast on the water tank span only). When the ballast mass increases the water tank span moves towards the wing tip. Therefore the mass force resultant arm with respect to the glider plane of symmetry increases. The aerodynamic force resultant arm is not affected by the water ballast, but the subtracting mass forces moment increases with the ballast tank span.

To illustrate the overall water ballast influence on the wing loads the calculations of wing normal bending moment for the gust of + 15 [m/s] have been completed and results listed in Table II.

For the ballasted configuration the bending moment at first increases, but finally decreases again, owing to the influence of the water tank span and limited all-up mass. For the ballastless configuration, the bending moment again increases, even though the mass remains constant, because of the increase in V_{RA} - see 3 above. This configuration becomes the critical one when ø exceeds about 0.65.

4.2. Tailplane

The tailplane loading consists of:

- force for trim,
- incremental force due to the gust action or elevator deflection,
- mass force.

The force for trim depends on the glider aerodynamics and geometry and is individual for the type under consideration.

The basic influence of the water ballast variations is reflected in the incremental force and mass force proportional to it. To find the influence of the water ballast amount the incremental force should be mainly examined.

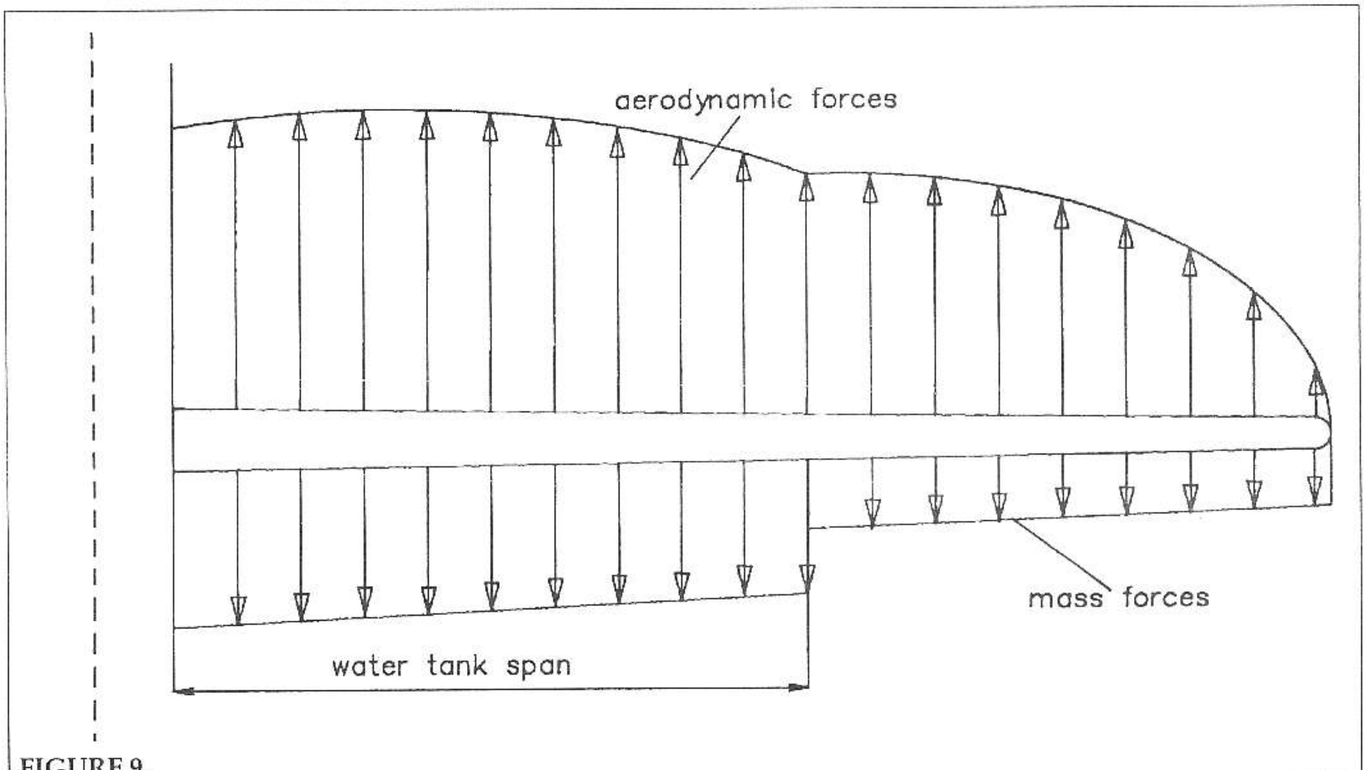

FIGURE 9.

TABLE II

Wing normal bending moments in the wing-to-fuselage plane of SZD-55 sailplane [N*m]

Loading case: gust of + 15 [m/s]

Mass ratio : ø	0	0.181	0.363	0.544	0.725	0.907
Ballasted configuration	18197	20183	21442	21543	20839	18044
Ballastless configuration	18197	19083	19904	20694	21450	21781

4.2.1. Gust cases

The incremental tailplane force is:

$$\Delta P_{Hgust} = \frac{1}{2} \bullet \rho_o \bullet k \bullet a_H \bullet S_H \bullet \left(1 - \frac{d\varepsilon}{d\alpha}\right) \bullet U \bullet V$$

where :

a_H - slope of the tailplane lift curve,

S_H - tailplane area,

$\frac{d\varepsilon}{d\alpha}$ - wing downwash near the tailplane.

The variations of the water ballast mass ratio ø influence on the factor k and airspeed V, so the incremental force variation can be expressed by means of the factor:

$$r_{UA} = \frac{(k \bullet V_{RA})_{ø \neq 0}}{(k \bullet V_{RA})_{ø = 0}} \quad \text{for } U = \pm 15\ [m/s]$$

and

$$r_{UD} = \frac{(k \bullet V_D)_{ø \neq 0}}{(k \bullet V_D)_{ø = 0}} \quad \text{for } U = \pm 7.5\ [m/s]$$

The values of r_{UA} and r_{UD} versus mass ratio ø for SZD-55 sailplane are plotted on Figure10.

4.2.2. Maneuvering case

The maneuvering incremental force is:

$$\Delta P_{Hman} = \frac{1}{2} \bullet \rho_o \bullet aH \bullet \frac{d\alpha_H}{d\beta_H} \bullet \beta_H \bullet S_H \bullet V^2$$

where:

α_H - tailplane incidence,

β_H - elevator deflection angle increment

The incremental force variations depend on V^2 value, so the variation factor is :

$$r_{MA} = \frac{(VA^2)_{ø \neq 0}}{(VA^2)_{ø = 0}}$$

and

$$r_{MD} = \frac{(V_D^2)_{ø \neq 0}}{(V_D^2)_{ø = 0}}$$

The values of the functions: k_{MA} and k_{MD} versus ø for SZD-55 sailplane have been plotted on Figure 11.

4.3. Fin and rudder

To define the influence of the water ballast on the fuselage load the complex calculations should be carried on since:

- the tailplane force for trim depends on the aerodynamics and geometry of the glider,
- the mass distribution on the fuselage depends on the cockpit loading conditions,
- the resultant accelerations of the particular glider components depend on the linear and rotational movement introduced by the tailplane or fin and

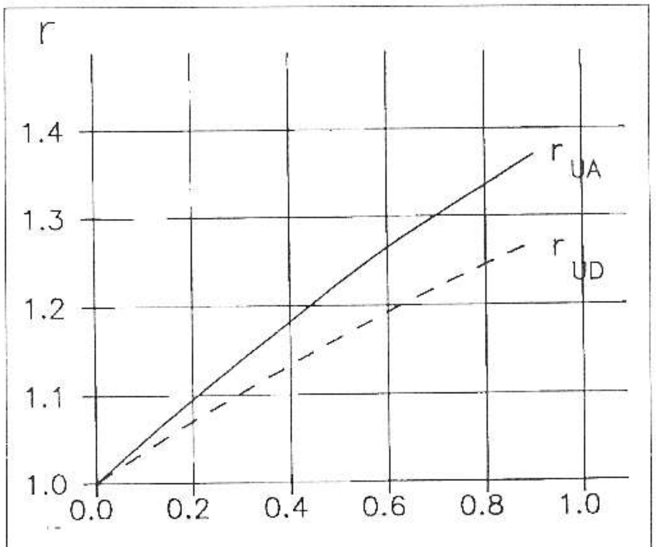

FIGURE 10.

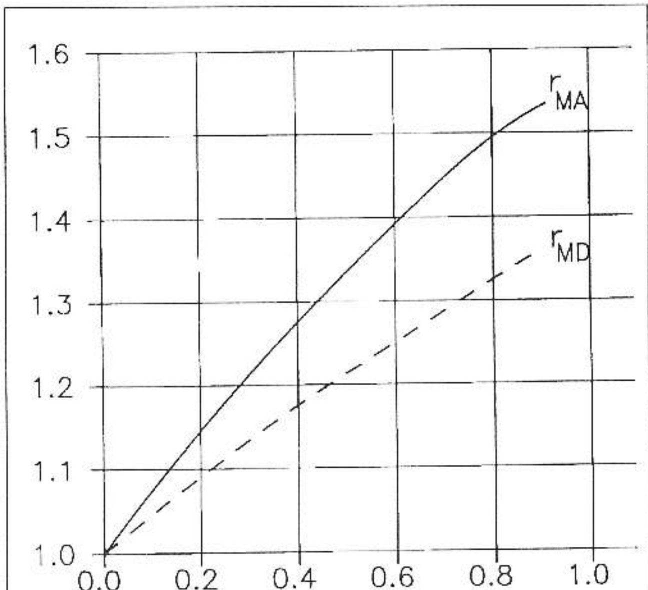

FIGURE 11.

TABLE III
Fuselage vertical bending moments of SZD-55 sailplane for the wing-to-fuselage rear fitting plane [N*m]
Loading case: vertical gusts

Mass ratio : ϕ	0	0.907
Gust of + 15 [m/s]	8002	6600
Gust of + 7.5 [m/s]	8194	7121

TABLE IV
Ground reaction on the wheel of SZD-55 sailplane [N]

Mass ratio : ϕ	0	0.181	0.363	0.544	0.725	0.907
R_G	12400	13250	14020	14900	15700	16110

rudder incremental forces.

With respect to the above the influence of the water ballast variation on the fuselage loads is a multi-parametric function which requiresindividual analysis for the particular loading cases.

As an illustration the fuselage vertical bending moments for SZD-55 sailplane as a function of mass ratio ø (in the plane of wing-to-fuselage fitting) is listed in Table III.

The listed values show evident increment of the bending moment for the ballastless configuration (ø = O) when compared with the full ballasted one (ø = 0.907).

4.5 Undercarriage

The ground reaction R_G acting on the rolling wheel of the undercarriage depends the loading energy E_l and chock-absorbing capability A_A of the undercarriage:

$$R_G = f(E_L, A_A)$$

The landing energy depends on the glider all-up mass and therefore is influenced by the water ballast amount. The shock-absorbing ability is independent of the mass.

The variation of the ground reactions with mass ratio for the SZD-55 sailplane is shown in Table IV. The full water ballast of 195 [kg] results the ground reaction increment of about 30 per cent.

5. CONCLUSIONS

The tendency to increase the water ballast amount in competition sailplanes follows from the resulting performance improvement especially in strong thermals.

On the other hand the increased water ballast results in decreased controlability and increased structural loads of the sailplane.

The degradation in the rolling controlability with increasing water is very noticable. The yawing controlability is less affected.

Increased water ballast produces a considerable increment in gust load factor.

The influence of the water ballast amount on the loads of the various sailplane components, as illustrated by the data for the SZD-55 sailplane, requires the structure to be strengthened. This, in turn, leads to higher mass of the empty glider and affects the cockpit loading possibilities.