INVESTIGATIONS OF AIRSHIP AEROELASTICITY

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Abstract

The aeroelastic behavior of a large airship at various flight conditions is considered. The study is focused on static aeroelastic problems, such as efficiency (reversal) of control, shift of aerodynamic center, change of other aerodynamic derivatives, and on dynamic problems such as flutter, gust response. The theoretical investigations use ABAQUS and MSC/NASTRAN finite element programs and updated ARGON multidisciplinary software package based on the polynomial Ritz method. A simplified airship mathematical model for ARGON calculations (and also for the conceptual design of a multifunctional modular wind tunnel model) is estimated using MSC/NASTRAN static nonlinear analysis and modal analysis. Stiffness parameters of the physical model are identified using an optimisation procedure. Main principles of the scheduled experimental investigations of dynamically/ elastically scaled and "rigid" aerodynamic models and their conceptual descriptions are presented.

1. Introduction

In contrast to other flying vehicles, the interaction of the elastic structure and the air flow (or aeroelasticity characteristics) for airships has some peculiarities:

- The most significant part of the airship structure – the envelope – is a thick body, for which lifting surface methods should be applied carefully.
- The envelope stiffness characteristics significantly depend on the difference between the inner and outer gas pressure. That leads to a complex dependence of aeroelastic properties on altitude and pitch angle.
- The larger the airship, the smaller is the aerodynamic lifting force relative to the buoyancy force.
- At high speeds essential envelope deformations are possible, which may lead to a loss of shape and stability.
- The density of the airship structure is in the same range as the density of the surrounding air. Hence the effect of the air virtual masses on elastic structure oscillations has to be taken into account.
- The inner gas influences various elastic modes in a different manner, which complicates the schematisation of the airship in a mass-inertia model.

2. Elastic mass model of the airship, modal analysis

The computational elastic mass model for solving aeroelastic problems is based on the finite element method (FEM). One of the main particularities is the envelope tensioned under inner gas pressure. The inertia forces acting on the keel are distributed to the bottom of the envelope and via catenary cables to the top of the envelope.

The FE scheme should take into account the varying inner gas pressure. Furthermore, the estimation of structural stiffness characteristics for each variant of

payloads, flight regimes and flow conditions requires solving physical and geometrical nonlinear problems.

Such special problems lead to a significant complication of the computational methods usually used for aeroelastic investigations, since the structural nonlinear effects can only partially be considered in the specific software. This also causes difficulties in experimental methods due to evident problems with the design of physical models.

For the development of the computational model, FEM software as MSC/NASTRAN and ABAQUS are used, which have a high potential for modelling the nonlinear behavior of the structure under static loading.

For example in fig. 1 the FE model of the airship is presented. This model is developed using the PATRAN preprocessor for MSC/NASTRAN and ABAQUS computations. In this model both standard finite elements (plates, beams,…) and specialised nonlinear elements (for example rod elements with zero compression stiffness) are used. The model has approximately 30000 degrees of freedom, 6500 nodes and 7450 elements.

Based on this model, modal characteristics of the airship structure are calculated. For the lowest eigenmodes the envelope cross-section does not significantly change. With sufficient accuracy these lowest modes could be described as "beam" modes. In fig. 2 one of these lowest eigenmodes is shown.

A simplified elastic mass model only consisting of beams and plates is built. Its stiffness and modal characteristics are comparable to the same properties of the complex FE model for the lowest modes. The simplified model is very suitable not only for parametric computations, but also for the construction of a physical model for wind tunnel tests.

A nontraditional approach for the design of a physical model is used. The elastic mass characteristics is determined from the inverse design problem using known response, such as influence coefficients matrix (ICM), eigenmodes and -frequencies, response on harmonic influence. As known response the

results of the nonlinear FEM computations of the complex airship model are used. The inverse design problem is then solved with the optimisation block of the MSC/NASTRAN software.

The initial structure is estimated based on nonlinear computations of ABAQUS and MSC/NASTRAN. On the first optimisation stage the elastic mass characteristics of separate structural parts (keel, envelope, empennage,…) are identified. On the next stage the elastic connections of these parts are determined.

In this way a simplified computational beam model is developed. Its FE characteristics sufficiently match the ones of the complex airship model. In fig. 3 one of the lowest eigenmodes of this beam model is presented, which corresponds to the mode of the complex FE model shown in fig. 2.

Based on such a simplified model a computational scheme for the multidisciplinary software package ARGON is developed (figs. 4-5).

3. Aerodynamics

Well-proven linear methods for computing the ideal gas potential flow are used in the ARGON system to evaluate the aerodynamic forces. The aerodynamic model of the airship is composed of slightly cambered interfering lifting surfaces, which are nearly parallel to the undisturbed flow (fig. 6). In this case the envelope is modelled by a "cross" scheme consisting of the projection of the envelope thick body on the horizontal and vertical planes.

The panel method, based on the velocity potential, is used to analyse quasi-steady air loads. The unsteady aerodynamic forces in a subsonic flow are computed by the doublet-lattice method to solve the integral equation of the acceleration potential.

The redistribution of loads along the envelope length requires a more accurate computation of the airship aeroelastic characteristics. In this case body aerodynamics (also based on the velocity potential) is used for

the envelope, whereas the empennage is still described by lifting surfaces.

4. Static aeroelasticity

A static aeroelasticity analysis includes the following main problems:

- reversal of control and aeroelastic divergence;
- redistribution of quasi-steady aerodynamic loads due to structural elastic deformations;
- influence of structural elasticity on the stability and control characteristics of the airship.

In the ARGON package the influence coefficients method is used to analyse the static aeroelasticity. The following general remarks summarise the essential features of the method. Discrete aerodynamic forces f_a are related to the distribution α_t of the angle of attack on the panels via the aerodynamic influence matrix A:

$$f_a = qSA^{-1}\alpha_t$$

where q is the dynamic pressure and S the diagonal matrix of the panel areas.

As above, the relation between the external force vector f and the elastic twist angles α_f can be written as

$$\alpha_f = C^{\alpha f} f$$

where $C^{\alpha f}$ is the structural elastic influence matrix which is determined by the polynomial Ritz method. In addition to the aerodynamic loads the gravity and inertia forces

$$f_m = -(g + \omega_z V)M_F$$

are applied to the airship, where g is the gravity acceleration, V the flight speed, ω_z the pitch rate (Wz) and M_F the vector of point masses. Taking into account that

$$\alpha_t = \alpha_r + \alpha_f, \; f_a = qS\Delta P$$

where α_r is the vector containing the rigid body angles of attack on the panels and ΔP is the vector of the pressure differences on the panels, the following equation can be derived:

$$(A - qC^{\alpha f}S)\Delta P = \alpha_r - C^{\alpha f}(g + \omega_z V)M_F \quad (1)$$

From this system of linear equations, the pressure distribution over an elastic airship for a given rigid-body motion and a given mass distribution can be determined. The static aeroelasticity characteristics can be computed using this pressure distribution.

The right-hand side of system (1) is presented as a linear combination of principal vectors; the general solution will then be a linear combination of the corresponding principal solutions. The distributions of angles of attack over the airship at unit rigid body angle of attack α_r, unit pitch rate ω_z, unit normal load factor n_y, specified angles of twist and camber and unit symmetric control deflections δ (d) are considered as principal vectors for the longitudinal motion. The pressure distributions for unit sideslip β, unit roll rate ω_x (Wx), unit yaw rate ω_y (Wy) and unit antisymmetric control deflections are considered as principal vectors for the lateral motion.

In each case the system (1) is solved and only the right-hand vector α is changing. The derivatives of the aerodynamic coefficients, C_y^α, M_z^α,..., M_x^δ,... of an elastic airship are computed by appropriate integration of the corresponding pressure distribution. The computed pressure distributions are further used to analyse the quasi-steady loads.

In order to estimate some divergence and reversal characteristics, the derivatives of the normalised aerodynamic coefficients as a function of the dynamic pressure are computed for a set of Mach numbers. The increase of certain derivatives (for example the lift slope coefficient c_y^α) shows some divergence tendency, and the decrease of the control derivatives (for example $m_x^{\delta_a}$ the roll moment derivative due to an aileron deflection) shows some reversal tendency. The influence of the structural elasticity on the aerodynamic

coefficients is estimated via a relative value ξ, which is equal to the ratio of the derivatives of the aerodynamic coefficients for an elastic airship and a "rigid" one, for instance

$$\xi_{c_y^\alpha} = \frac{c_{y\,el}^\alpha}{c_{y\,rig}^\alpha}.$$

The relative shift for the aerodynamic center $\Delta \bar{x}_F = \bar{x}_{F\,el} - \bar{x}_{F\,rig}$ is determined.

According to the static aeroelasticity method, two types of characteristics are considered: the characteristics of a constrained and the ones of a free structure (without and with taking into account the mass distribution). The joint consideration of these derivatives enables to evaluate the mass distribution influence on the static aeroelasticity characteristics.

Some static aeroelasticity characteristics are drawn in figs. 7-10 for a symmetrical case. The following results can be seen:

- The lift slope coefficient is greatly decreased due to the structural elasticity (fig. 7).
- The forward shift of the aerodynamic center position is also very important (fig.8). That is on the one hand due to the increase of the lift on the forward part and on the other hand due to the decrease of the lift on the rear part of the elastically deformed airship.
- The control surfaces effectiveness on the lift and on the pitch moment (figs. 9,10) is essentially decreased.

The main results for an antisymmetrical case (aerodynamic derivatives and elastic deformations along the airship length) are shown in figs. 11-13. The influence of the structural deformations on the aerodynamic characteristics is very significant, even though the empennage is here considered as an absolutely rigid part.

5. Flutter

The equation of oscillations in modal generalised coordinates $\bar{q}$ in matrix form can be written as

$$\left[\lambda^2 C + \lambda(\rho V D + D_0) + (\rho V^2 B + G) \right] \bar{q} = 0$$

where $\lambda = g + i\omega$ is the complex eigenvalue of the equation, ρ the air density, C and G the structural inertia and stiffness matrices (from the plate-beam polynomial Ritz method), D_0 the structural damping matrix (viscous damping assumption) and $D(Sh)$ and $B(Sh)$ the unsteady aerodynamic damping and stiffness matrices depending on the Strouhal number or reduced frequency $Sh = \omega b / V$ (b denotes a reference length). The aerodynamic matrices at specified Sh values are computed using the Doublet Lattice Method (DLM).

The eigenvalues $\lambda = g + i\omega$ depending on V are found by the QR algorithm. The real part g is the damping coefficient and the imaginary part ω is the angular frequency of the corresponding eigenoscillation. Positive damping means that the amplitude increases in time, which leads to a flutter instability. The flutter criterion for ARGON is $\delta = 0$ at $\omega > 0$ and $V > 0$ (similar to the PK-method in MSC/NASTRAN).

In fig. 14 dependencies of the frequency $f = 2\pi / \omega$ and the damping coefficient on the velocity (V-f and V-g plots) for the antisymmetrical case are presented. The flutter speed is 96m/s. The corresponding flutter mode with a frequency of 0.18Hz, caused by interaction of 4-th and 6-th eigenmodes (first bending mode in horizontal plane and envelope/keel torsion), is shown in fig. 15 for phases of 0 and 90 degrees.

In the next phase of investigations it is necessary to take into account the flexibility of the link between the empennage and the rudders. Furthermore, the initial data concerning the stiffness and mass-inertia characteristics of the envelope and the keel have to be refined.

6.Gust response

The gust response of the airship is considered under quasi-steady assumption on the basis of the following equation:

$$C\ddot{\bar{q}} + (\rho VD + D_0)\dot{\bar{q}} + (\rho V^2 B + G)\bar{q} = \rho V Q^w w$$

where Q^w is the effectiveness of the gust on the generalised coordinates and w is the gust velocity.

According to the Transport Airship Requirements (TAR) the gust velocity is given by the expression

$$w = 0.5 w_m (1 - \cos(\pi x / H))$$

where w_m is the maximal gust velocity ($w_m = 7.62$m/s for $V = 33.3$m/s and $w_m = 10.67$m/s for $V = 21.5$m/s), H is the gust gradient length ($L/4 < H < 244$m with the airship length L) and $x = Vt$ ($0 < x < 2H$) is the penetration distance.

On this stage we have considered the influence of the vertical gust on the load factor response at different points of the envelope (Ny1, Ny2, Ny3) and of the keel (Ny4, Ny5), see fig. 4. On the upper picture in fig.16, the gust velocity is presented. The second picture in fig.16 gives the load factor Ny0 at the center of mass. The third and fourth pictures, fig.16, show the load factors on the envelope and keel mass points. In the same manner the distribution of the loads on the envelope, the keel and the empennage can be estimated.

7. Aeroservoelasticity

The process of dynamic interaction between the airship elastic deformations and the automatic control system (ACS) can be stable or unstable, favorable or unfavorable. These phenomena are studied via an aeroservoelasticity investigation. The main problem is the analysis of dynamic stability with or without an airflow in the frequency range of the elastic oscillations of the structure. An important question is, whether the required level of oscillations damping, decrease of turbulent loads and load factors can be achieved, using additional ACS's loops. A high efficiency of ACS can be obtained via separation of desirable and suppression of undesirable signals. In the same way, unfavourable phenomena in aeroelastic interaction can be avoided. For that purpose we

have, as in the aviation industry, some opportunities:

- ACS transducers can be placed relatively to nodes and antinodes of the corresponding mode shape of the structure oscillation.
- Control laws can be corrected, and additional filters can be installed in corresponding sections of ACS, using ordinary engineering methods, optimal control methods, analytical controller design etc.
- The rudder actuators and control links characteristics can be modified.

Additional filters in ACS sections can substantially influence the airship stability and controllability characteristics as rigid body. Therefore the problems of aeroelastic interaction have to be solved in cooperation with flight dynamics specialists. A digital ACS can lead to additional aspects of aeroelastic interaction.

Theoretical and experimental investigations of aeroelastic interactions of an airship with ACS are performed (as for other flying vehicles) in time or frequency domain. For closed loop investigations in the time domain known disturbance input (test function) is applied and the ACS's influence on airship dynamic characteristics is estimated, based on transition processes analysis. Investigations in the frequency domain are based on determining and analysing the frequency characteristics.

Aviation experience shows that for the analysis of aeroelastic stability of flying vehicles with ACS investigations in the frequency domain are preferred.

Most effective is a combination of theoretical and experimental investigations, when frequency characteristics of ACS's sections can be measured, and based on these measurements parametric calculations can be performed.

8. Future experimental investigations

The design of an airship physical model is based on a simplified approach. Such a multifunctional model is intended for the experimental investigation of the aeroelastic

behavior and loading of the airship in a subsonic wind tunnel (figs. 17-21).

The model should be designed and fabricated using a modular approach allowing three different configurations:

1. a dynamically scaled model;
2. an elastically scaled model;
3. rigid aerodynamic models.

Whereas the first model is used for flutter, gust response, buffeting and aeroelastic stability investigations including an automatic control system, the second and third models can be utilised for estimating the influence of elastic deformations on the effectiveness and the hinge moments of the rudders, on the shift of the aerodynamic center, on other aerodynamic derivatives and on the aerodynamic loads.

The full elastically/dynamically scaled airship model is designed with a section/beam scheme and consists of two dynamically scaled parts, the envelope and the keel, with an elastic connection in-between. Each part is composed of an elastic spar and of rigid sections attached to this spar (fig. 17).

The spars have a variable cross section and three distributed stiffnesses: bending stiffnesses in the vertical and horizontal planes as well as a distributed torsional stiffness. The sections of the rigid model represent the external aerodynamic shape of the envelope and the keel. Each section is attached to the spar of its respective part (envelope or keel) in such a manner that it does not disturb the deflections of the bending and torsional spar.

The sections consist of a middle frame and skins. Additional point masses are fixed on the frame to provide the given mass and mass inertia distribution along the envelope and the keel. The additional masses can also be fixed directly to the spar. Three stabilisers, the upper, port and starboard ones, are fixed through springs to the spar; the lower stabiliser is connected to the keel spar via hinges and bearings (fig. 18). The stabilisers themselves are made using either a similar simplified structural scheme or a plate approach (fig. 19).

The rudders are fabricated as rigid parts and fastened by hinges. They are similar to the full-scaled rudders regarding the mass, the

location of the center of gravity and the moments of inertia. The stiffness of the actuators driving the rudders is simulated using springs. It is foreseen to vary the stiffness of the springs used for the actuators and for the attachment of the stabilisers to the envelope.

The elastic and mass data of the envelope as well as the flexibility of the link between the envelope and the keel depend on the airship flight regime (altitude, pitch angle) and configuration (heavy or light).

Therefore, the fabrication of several replaceable envelope spars, of complete series of interchangeable springs and of removable additional masses is foreseen. The spars, the sections, the skins and the frames as well as the stabilisers will be fabricated using composite materials. The scheme of this multifunctional model will be revised after future computational investigations using updated initial data.

In the wind tunnel, the parametric research of the flutter modes of an envelope/keel configuration including the stabilisers and rudders oscillations can be carried out.

The tests will be carried out using a free-free mounting device close to the free flight conditions of the full-scale airship at the pitch angles of $\varphi = 0°$ and $\varphi = +15°$ (fig. 20). For the same states the unsteady loading acting on the airship during flight and depending on the gust conditions will be investigated.

The second configuration of the model, the elastically scaled one, is intended for performing static aeroelasticity investigations. The model is equipped with two strain gauge balances: the first one is situated near its center of gravity whereas the second one is installed to measure the rudder hinge moments. The same rigid support can be used for the tests with the dynamically scaled model in order to investigate the overall aerodynamic characteristics due to the effect of vertical gusts.

The third configuration of the model is consisting of the rigid envelope model rigidly attached to the rigid keel model. The envelope of the third (and also the second) model is

drained for the measurement of the static pressure distribution. The dynamic pressure transducers will be located on the envelope for buffeting investigations. Some silk tufts and a silk thread grid behind the model are used for the visualisation of the flow. For this configuration of the model the parametric research of stabiliser flutter at non-zero pitch angle and different yaw angles will be carried out.

For gust investigations, the next operations are planned in a subsonic wind tunnel:

- On the rigid aerodynamic model for different angles of attack, yaw and roll, we will carry out
  - flow separation zone investigations,
  - flow visualisation using surface tufts,
  - strain gauge balance measurements,
  - pressure distribution measurements at unsteady change of flow conditions near to boundary of unseparated flow,
  - modelling of unsteady flow conditions using an airfoil cascade oscillating in harmonical flow.
- On the dynamically scaled model on a floating suspension system, we will investigate
  - the influence of vertical harmonical or single gust for correction of the mathematical airship model,
  - influence of asymmetrical gust (roll reaction) and
  - the influence of side gust.

For unsteady loads and buffeting investigations it is planned to estimate the flow separation zone using tuft visualisation and video recording in silent atmosphere and in gust flow. Based on the principal visualisation scheme for unsteady aerodynamic loads, pulsation measurements should be performed. The response of the dynamically scaled model to unsteady influence and buffeting boundary of control will be measured for given (agreed) ranges of flow speeds, angles of attack and yaw angles.

The above listed model configurations and the necessary volume of experiments in the wind tunnel is the result of previous analysis of possible aeroelastic problems for the airship which has to be refined before the experimental phase can start. The results of the analysis decide on the necessity of experiments.

9. Conclusion and future work

In this paper, first results of airship aeroelasticity investigations are presented. Calculations on a full-scale model have been performed and some simplified numerical models have been developed. The conceptual design of a physical model is outlined.

The airship aeroelasticity problem greatly depends on the stiffness characteristics of the empennage, the attachment of horizontal and vertical stabilisers to the envelope, the stiffness of the rudders and actuators. On the next phase it is necessary to refine these data. Furthermore, tools for theoretical aeroelasticity investigations have to be adapted to airship problems:

- virtual masses have to be included in the investigations, both for dynamic calculations and for the design of the physical dynamically scaled model;
- the aerodynamics computations for volume bodies in steady and unsteady oscillatory flow have to be improved;
- unsteady gust loads need to be analysed for volume bodies;
- structural/aerodynamic coupling in the MSC/NASTRAN and ARGON software packages has to be refined.

The parameters for the simplified models (ARGON/physical) have to be identified for various airship configurations and flight regimes. With these parameters the physical models (dynamically scaled, elastically scaled, "rigid" aerodynamic) and their suspension systems in the wind tunnel, including flutter and strength/stress analysis for achieving tests safety, have to be designed.
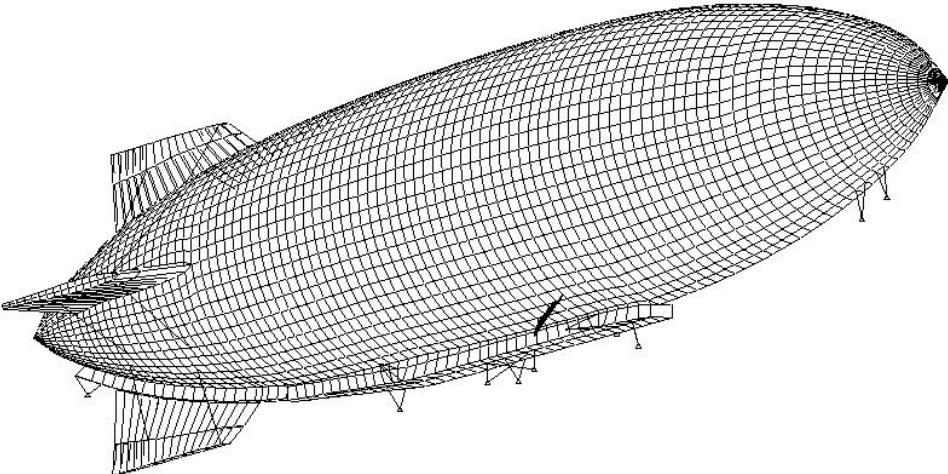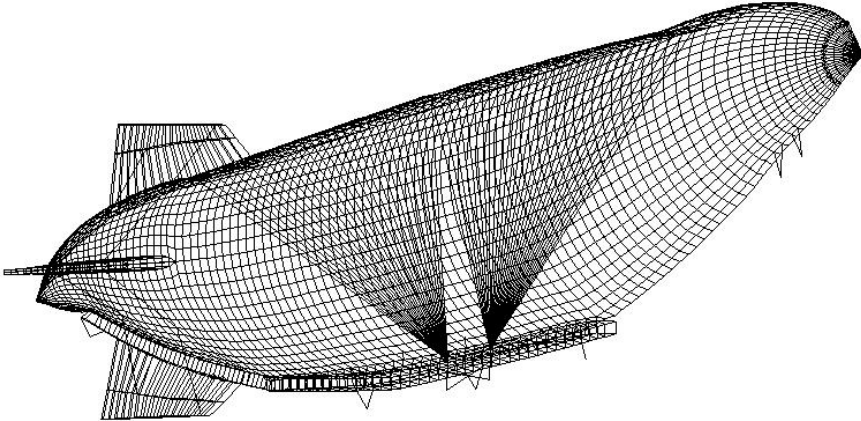
Fig.1. FE model of the airship
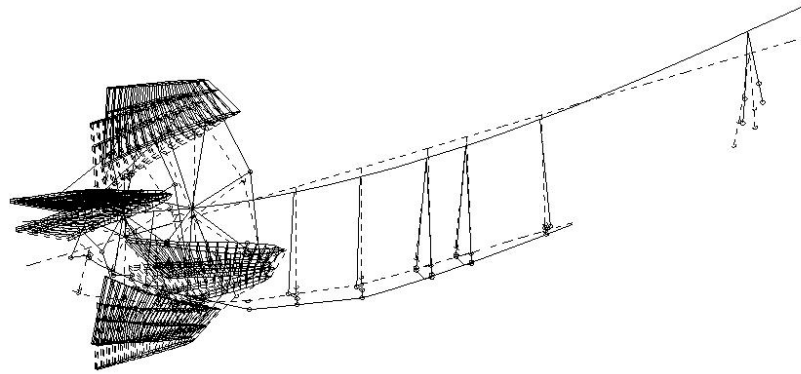
Fig.2. Modal analysis result of the FE model

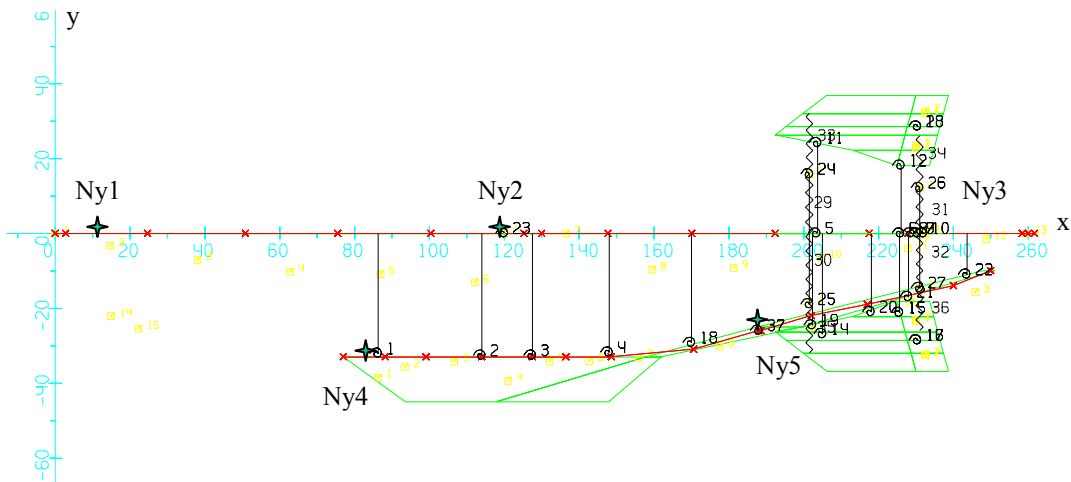Fig.3. Modal analysis result of the simplified beam model of the airship

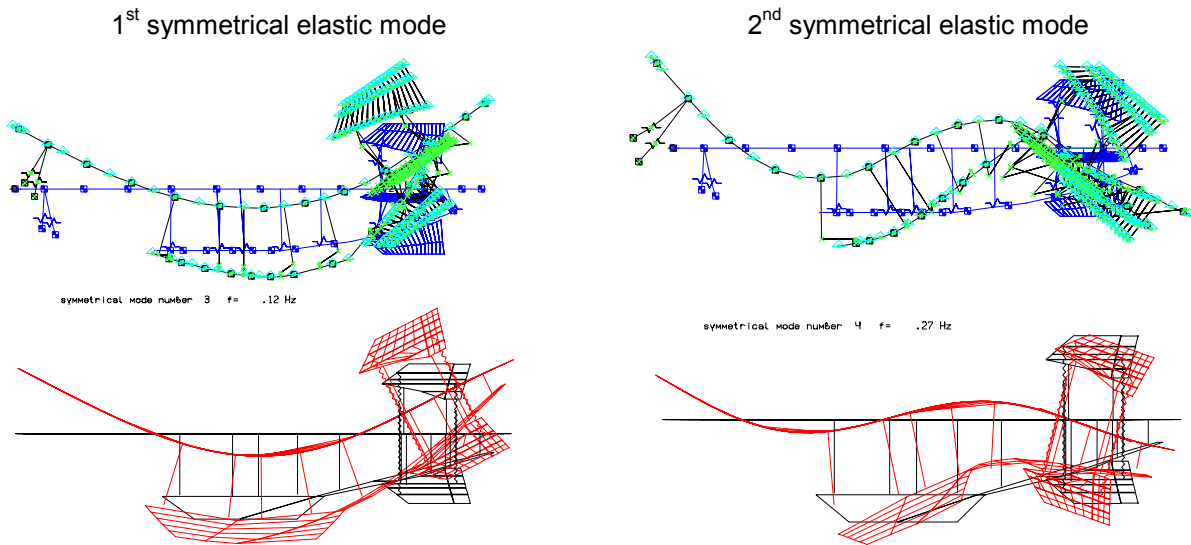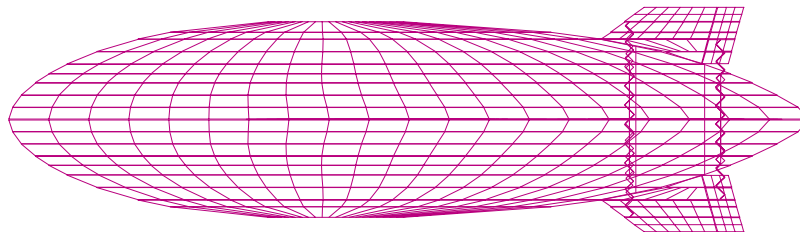Fig. 4. Simplified beam-plate model of the airship structure for ARGON (side view)

1st symmetrical elastic mode

2nd symmetrical elastic mode

symmetrical mode number 3 f= .12 Hz

symmetrical mode number 4 f= .27 Hz

Fig.5. Comparison of NASTRAN and ARGON beam models

a) Plan view

b) Side view
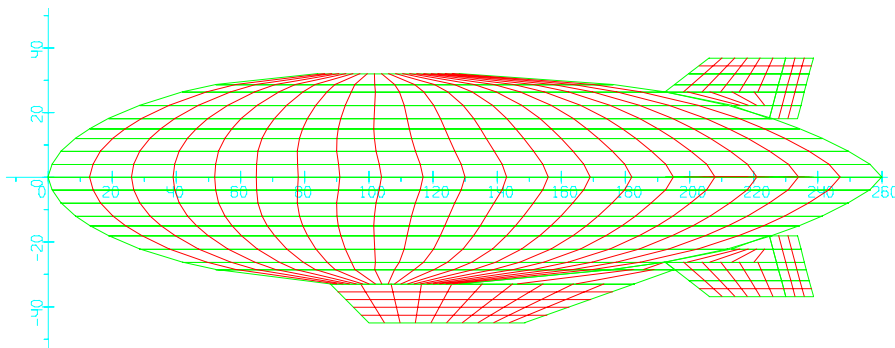
Fig. 6. Aerodynamic model
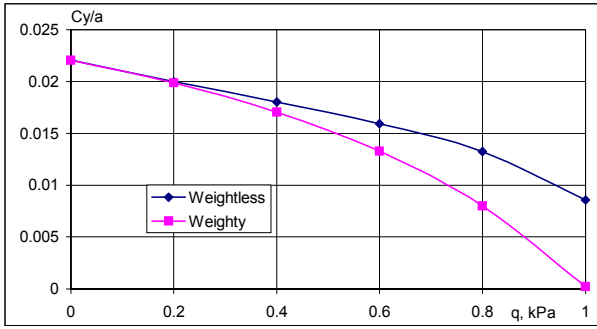
Fig.7. Lift slope coefficient versus dynamic pressure
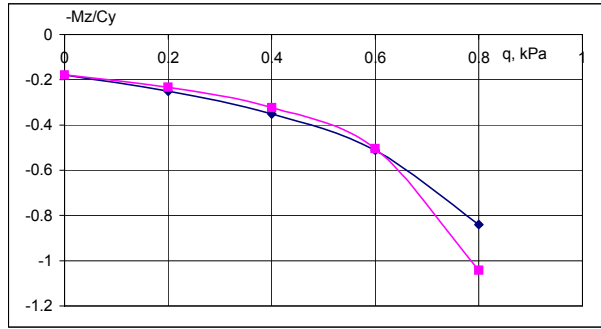
Fig.8. Aerodynamic center position
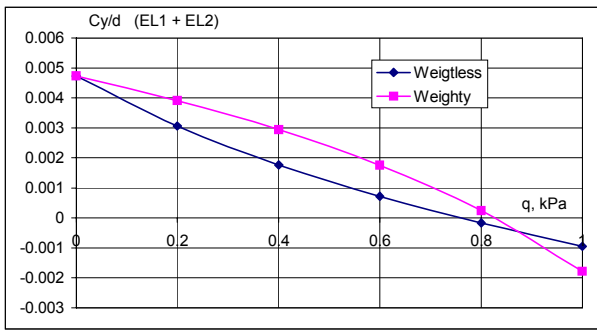
Fig. 9. Derivative of lifting force coefficient due to rudder angle versus dynamic pressure
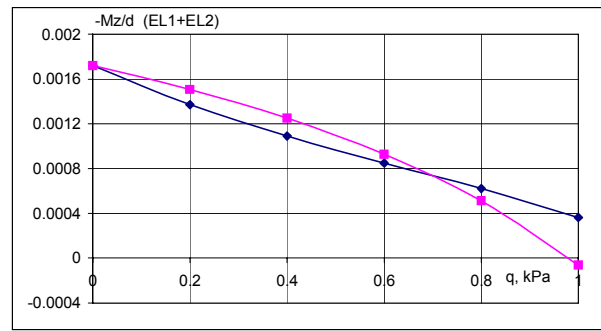
Fig. 10. Derivative of pitch moment coefficient due to rudder angle versus dynamic pressure
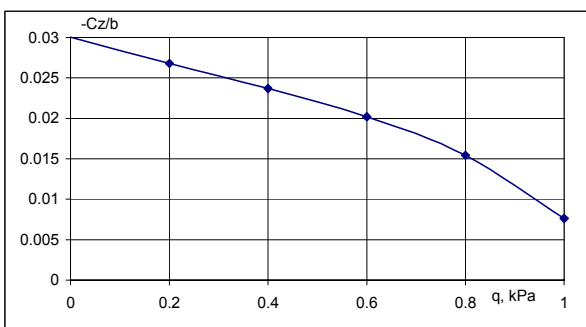
Fig.11. Derivative of side force coefficient due to yaw angle versus dynamic pressure
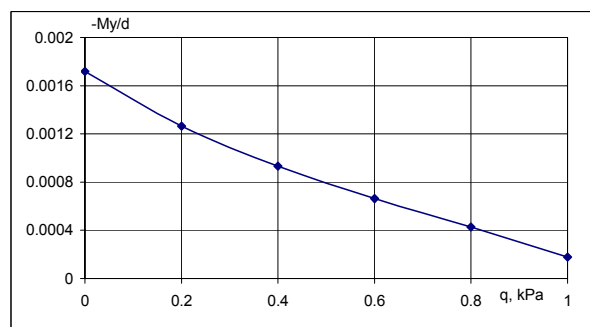
Fig.12. Derivative of yaw moment coefficient due to rudder angle versus dynamic pressure
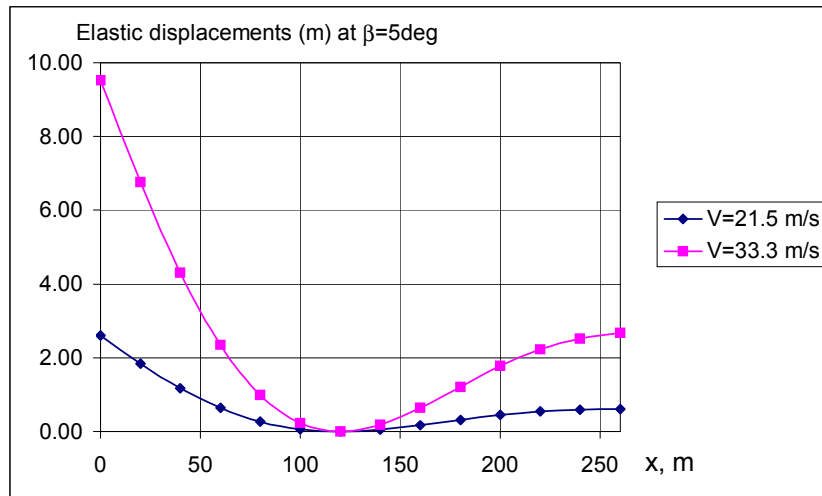
Fig.13. Lateral elastic displacements along the airship flying with sideslip angle
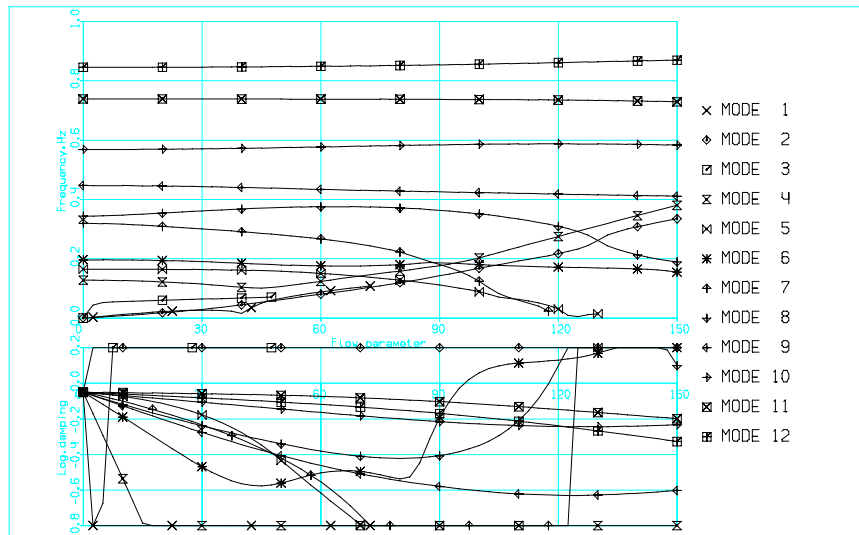
Fig.14. V-f and V-g plots: antisymmetrical case

Flutter mode (phase 0 deg)   Flutter mode (phase 90 deg)
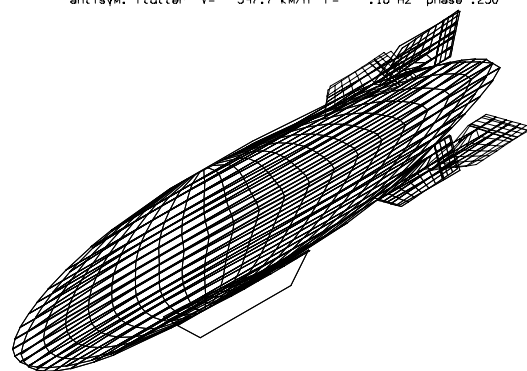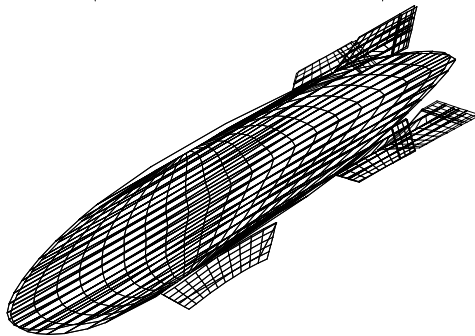
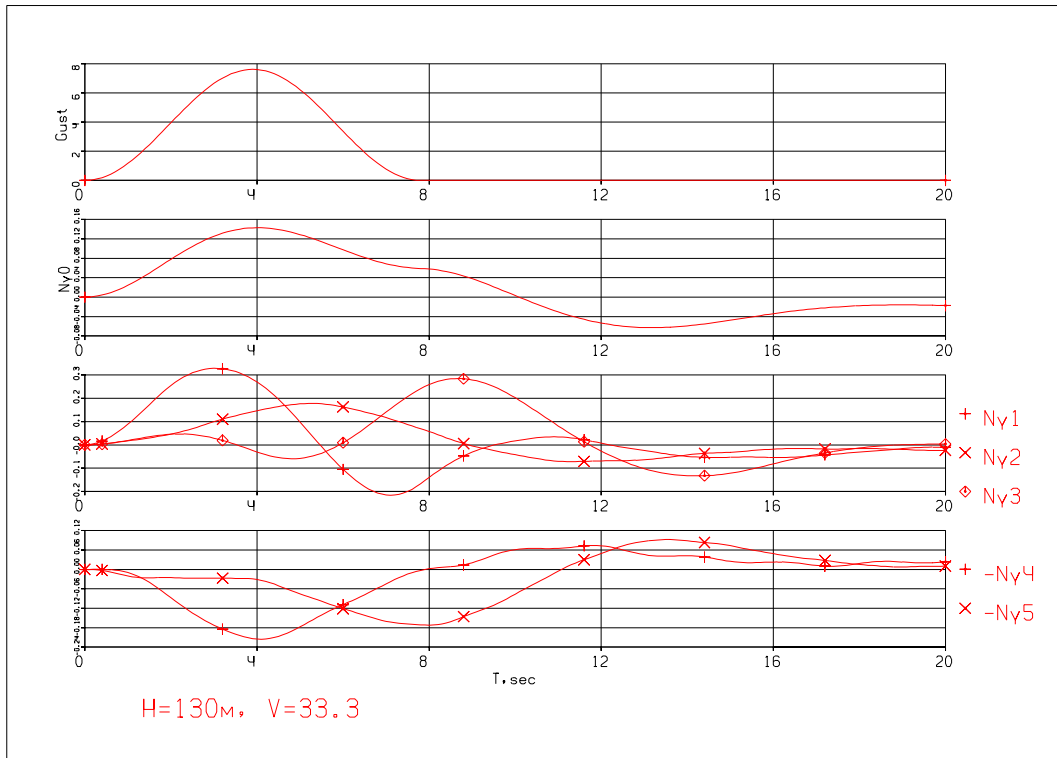

Fig.15. Flutter mode shape at two phases of oscillation

Fig.16. Accelerations at various points of the airship structure due to gust

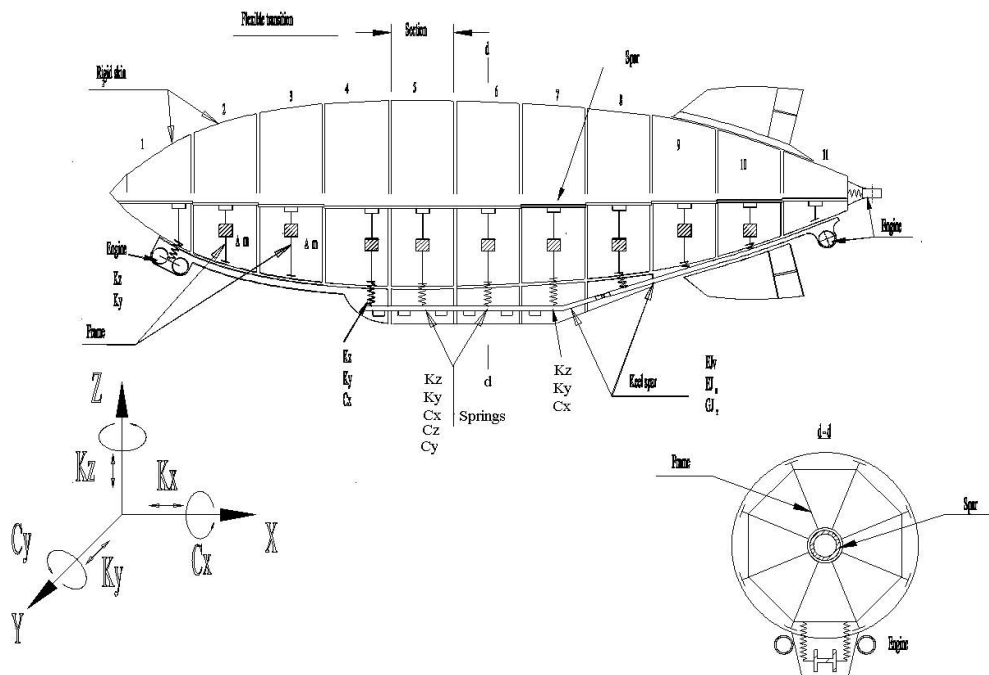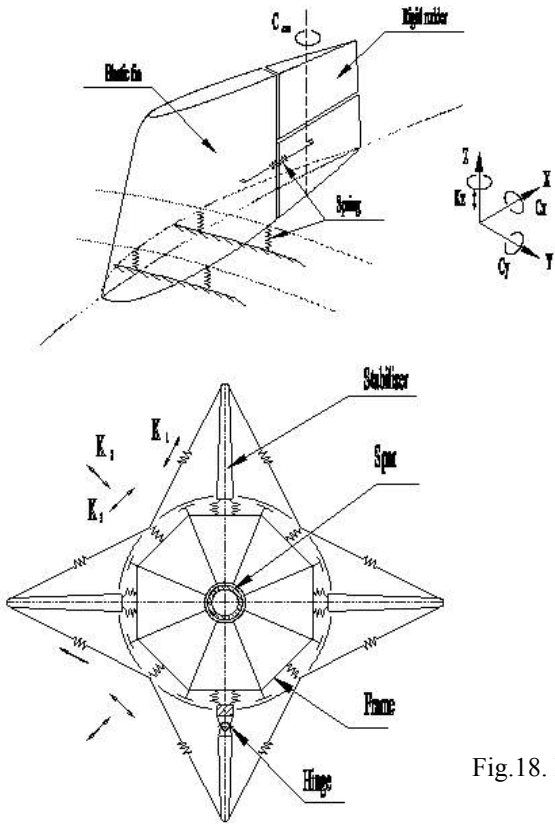Fig.17. Conceptual design of the simplified physical model

Fig.19. Main structure of the fin model
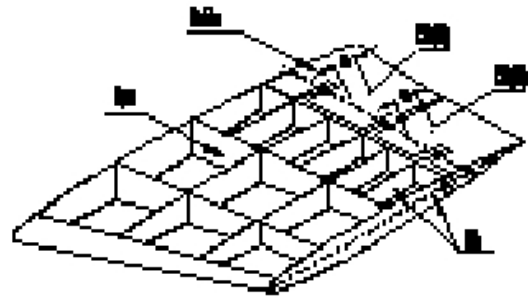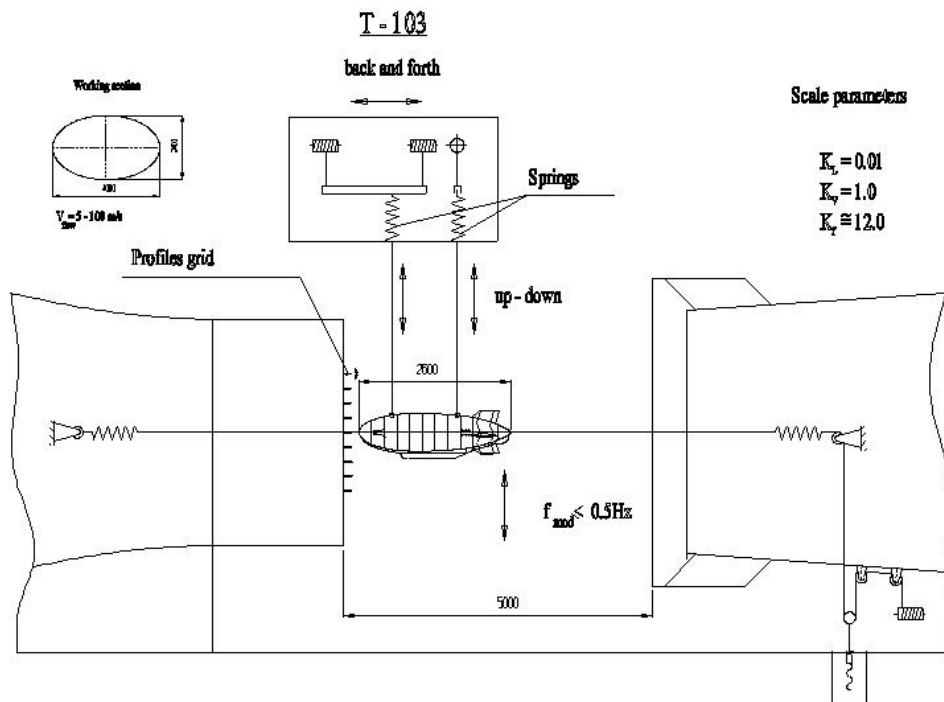
Fig.18. Empennage attachment

Fig.20. Suspension system of the dynamically scaled model