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THE DEVELOPMENT AND TESTS OF YAN'AN 2 LIGHT HELICOPTER

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ABSTRACT

Yan'an 2 designed by Chinese own is the first light helicopter having preliminary success in flight tests. This paper describes briefly its development, giving information and analysis on the design features, ground and flight tests in general and major dynamic problems.

Fig. 1 Yan'an 2 Light Helicopter

1. HISTORICAL BACKGROUND AND DEVELOPMENT PROGRAM

Although centuries ago the Chinese were the first to fly a helicopter, of couse, it was not a real helicopter rather a toy, which has become known as the Chinese top, while appearance of the real helicopter in China was so late, that the second generation of helicopter, which powered by turboshaft, were widespread in the world.

In 1958 the helicopter Z-5 was started to build in China. In the mid 1960's the helicopter Z-5 with all-metal main rotor blades was turned out in serial production, and helicopter research work on some topics, for example, the vortex theory, remarkable achievements had been made.

At that time the self-design work, which is a powerful motive force of helicopter development, was not launched. There were not practical experiences about helicopter aerodynamics, dynamics, design of the main components such as main rotor, tail rotor, gear boxes and systems. In addition, the understanding of management of a helicopter engineering system also was very poor.

In this situation we started to design a light helicopter named Yan'an 2. The design philosophy could be summarized as follows.

1. By way of self-design, manufacture and test we tried to know, analyse and treat all-round problems which would be encountered in the developing process in order to foster the design ability in China.
2. We tried to provide a prototype of light helicopter which could be satisfied the user's requirements preliminarily.

According to the design philosophy, in 1965 the development program for the Yan'an 2 was started. The 691 piston engine, main gear box J91 and tail rotor gear box WJ91 were prepared by 331 Co. Part of the academic staff and students of North-West Polytechnical

Institute started to design the light helicopter. We had completed the layout project, the design of main rotor blades and hub, fuselage, landing gear, control system, tail rotor and tail rotor drive shaft, and we had carried out the aerodynamic calculation, the static and dynamic strength analysis. And some static, dynamic tests had been done.

Before Oct. 1967 the prototype 01 for static test and the prototype 02 for ground test had been prepared. Unfortunately the prototype 02 was damaged by ground resonance in the test.

After the accident we concentrated on the solution of ground resonance. At that time some tests about strength, vibration, fatigue were added. At the end of 1969 the trouble of the ground resonance had been eliminated successfully, and the ground running test on prototype 02 and the assemblage of prototype 03 were started.

In Dec. 1970 the Yan'an 2 helicopter following the collective of helicopter section was moved from Xi'an to Nanjing. After some improvments and tests the preliminary flight test of Yan'an 2 was completed successfully in 1975.

2. MAIN CHARACTERISTICS AND DESCRIPTION

2.1 General Characteristics

Engine

691 nine-cylinder radial piston engine

Take-off power and consumption	275hp, 260-280g/hp.h
Rated altitude with FZ-89 turbo-supercharger	3500m
Normal power and consumption	260hp, 225-270g/hp.h

Dimensions

Overall length	8.0m
Overall height	2.56m
Width (fuselage)	1.35m
Rotor diameter	10.0m

Solidity of main ortor	4.89%
No. of blades	3
Main rotor rotating speed	358rpm
Tail rotor diameter	1.8m
Solidity of tail rotor	9.91%
Tail rotor rotating speed	1912rpm
No. of seats	2
Weight and Performance	
Design gross weight	1155kg
Disk loading	14.7kg/m^2
Max. level speed	190km/h
Cruising speed	140km/h
Hovering ceiling OGE with FZ-89	3500m
Service ceiling	6300m
Range	230km
Endurance	2.3h
Max. rate of climb	7m/s

2.2 Basic Performance, Stability and Control

A fuselage model for wind tunnel tests was made, and the results of the forces and moments were obtained. Based upon the data of wind tunnel tests the basic performance, stability and control calculation were completed.

Fig. 2 shows the curves of the coefficients of the power required as well as the coefficients of the available power for various altitudes. The blade stall limit and the point of minimum power required, which corresponds the maximum climb speed, can be seen.

The flight envelope is plotted in Fig. 3. The curves indecate that the light helicopter Yan'an 2 can be used in the most territory in China.

The longitudinal, lateral and directional trims were calculated. The typical curves of longitudinal trim in hovering and forward flight are plotted in Fig. 4. The control margin is sufficient.

The result of stability shows that the stability of Yan'an 2 in hovering is better than that of the helicopter Z-5, which was confirmed by the pilots. The longitudinal motion in hovering is shown in Fig. 5.

The pitch, roll and yaw control sensitivity were calculated, and all of the results met the requirements of MIL-H-8501 as follows.

Displacement in degrees following one inch control input in hovering

Response	Pitch in 1 sec	Roll in 0.5 sec	Yaw in 1 sec	Max. roll rate °/S
MIL-H-8501	2.9	1.8	7.2	20
Yan'an 2	3.3	3.4	18	14

The test pilots was satisfied with the handing qualities of Yan'an 2.

2.3 Main Rotor

The rotor system is a three bladed fully articulated system having a diameter of 10m. The blade chord is 256mm giving a solidity of 4.89%.

All-metal main rotor blade has a nearly constant mass distribustion, constant chord and constant thickness ratio with a symmetrical airfoil section of NACA 0012. Each blade is made up of a light alloy spar, a steel blade root fitting, 12 trailing-edge pockets and the blade tip fairing. The trailing-edge pockets are filled with foam core.

In the design of rotor blade we used the experience which was obtained from the development of a small all-metal blade having a diameter of 5m for the rotor tower (see Fig.6).

The frequency tuning of the rotor blade is given in Fig. 7. The dynamic characteristics of the blade were proved by theoretical analysis, test in laboratory, ground and flight tests.

The full scale root section with a part of the rotor head was tested for fatigue under alternate bending load up to 40kg·m and centrifugal load up to 13000kg. Fig. 8 shows the fatigue test bench of the main rotor blade schematically.

The flutter margin of rotor blades was examined in theoritical analysis and ground running tests, in which the effective centre of gravity of the blade was removed rearwards artificially.

2.4 Tail Rotor

The tail rotor is of two bladed teetering semi-rigid type. The rotor hub has a built-in delta three hinge of 45°. The tail rotor blade is composed of a light alloy tubular spar, the contour of which is varied from circle to ellipse. The foam is filled around the spar. The fiberglass skin layer forms the outer shell. For erosion protection a stainless steel leading edge strip is bonded at the outer portion of the blade.

The tail rotor was tested on whirl test bench and in the wind tunnel for examining the dynamic characteristics and strength (see Fig. 9). The stress was measured in the tests. The alternate bending stress recorded on the spar was less than 1.3 kg/mm^2.

2.5 Power Plant

The nine-cyclinder radial piston engine 691 was modified from an aeroplane piston engine. The differences are that the 691 engine is mounted vertically and a forced cooling fan is added. For increasing flight altitude the engineer of the 331 Co. had developed a turbo-supercharger FZ-89.

2.6 Transmision System

The transmision system contains the main drive coupling, main gear box J91, tail rtotor gear box WJ91 and tail rotor driving shaft.

Main Gear Box J91 consists of the centrifugal friction clutch, overrunning clutch, tail rotor and accessory driving gear and one stage spur planetary gear.

Tail Rotor Gear Box WJ91 consists of a pair of spiral bevel gears operating at 90° shaft angle, yaw control input unit and pitch control shaft, as usually.

Both J91 and WJ91 were tested on a closed circuit bench at the 331 Co.

Driving Shafts. The main drive coupling has two universal joints and some rubber snubbers for tuning torsional natural frequencies. The tail rotor drive shaft consists of five parts. There are forward, intermediate and rear articulate shafts, stiff shaft, and a short shaft for changing shaft direction, which contains two universal joints and requires no intermediate gear box.

The main drive coupling and tail rotor driving shaft were designed and tested in institute. Fig. 10 shows the fatigue test bench of tail rotor driving shaft.

2.7 Airframe

The cabin and the conical tail boom are semimonocoque riveted aluminium structure. The centre section is welded of steel tubes, in which the piston engine and engine system are mounted (see Fig. 11).

The doors, engine fairings, upper and aft fuselage shells are made of laminated fiberglass. The horizontal stabilizer, which consits of a

D spar, aft section filled with foam, skins and tip panel, is all made of fiberglass. The tests of fiberglass products including the skin of tail rotor blades were passed perfectly.

The landing gear of Yan'an 2 is tricycle gear type with oleo-pneumatic shock-absorber. After the ground resonance the landing gear was redesigned significantly.

In the structure design foreign norms and requirements for example, FAR, BCAR and some from Soviet Union had been analysised and used. The design load factors is from 3.0 to −0.5. The structure was designed some conservatively, because the Yan'an 2 was our first design. We completed almost all the required calculations, static and dynamic tests, that ensured the success of Yan'an 2.

2.8 Control System

In cyclic and collective control system the push and pull rods are used. The control system of the tail rotor and the horizontal stabilizer are soft type. The horizontal stabilizer is linked with the collective control.

A hydraulic servo control system is adopted for the longitudinal and lateral input. The ZL-15 hydraulic booster and friction unit provided satisfactory feeling for pilots. The hydraulic system is not duplicated. If the system is failed, the pilots can also control the helicopter without any difficulty.

2.9 Fuel and Oil System

Fuel system consists of a tank having capacity of 110 litres, fuel shut-off valve, pump, filter, fuel pressure indicator, fuel contents indicator and warning light.

The lubrication system for the engine, the main gear box and turbo-supercharger are separated. The two coolers are cooled by the air drawn from engine cooling fan.

2.10 Electrical System

The electrical system (28v. DC) contains engine mounted generator having 1.5 kw and a battery having a capacity of 10 AH.

A VHF/AM transceiver is equiped.

3. ANALYSIS AND TESTS OF SOME DYNAMIC PROBLEMS

3.1 Ground Resonance

Ground resonance was encountered in ground test of Yan'an 2 helicopter and was solved successfully by means of mechnical impedance method.

For articulated rotor system the key of ground resonance is to know the response characteristics of the rotating blades in lagging motion, when the rotor hub is excited in the rotation plane.

The characteristics of the lag hinge damper is nonlinear, and was hamornic linearized for analysis. The actural parameters of damper were taken from dynamic test.

The fuselage supporting on the elastic landing gear has six freedoms. The more dangerous freedoms are in lateral, the rolling mode and the side shifting mode.

The main component of the landing gear is the oleo-pneumatic shock-absorber. Its dynamic characteristics are also nonlinear and difficult to determin analitically. Therefore, for calculating the dynamic characteristics of the fuselage-landing gear system, the dynamic tests of the oleo absorber and the wheels are necessary (see Fig.12).

We find that the description of the fuselage-landing gear system using equivalent system recommended by R.P.Coleman has some weakness, because the rolling mode and the side shifting mode are coupled. Using the mechanical impedance at centre of the rotor hub to describe the fuselage-landing gear dynamic system is more clear and reasonable.

For getting the dynamic characteristics we directly measured the impedance characteristics of the fuselage-landing gear system. The exciting force at hub centre was taken as input and the displacement of the centre was taken as output. The mobility of rotor with three hinged blades is calculated separately at the matching point. Nyquist stability criterion is then adopted to determine whether the ground resonance will occur or not.

The test installations are shown in Fig. 13, 14. The exciting forces were produced by a eccentric mass mounted on the main rotor head. The fuselage-landing gear system could be excited both in longitudinal and lateral. The rotor head was driven by a DC motor through a soft shaft linked with the main gear box. The exciting force could be calculated exactly. The displacements of the hub were measured by displacement sensors. The phase angle could be got by a azimuthal contact point. According to the driving force azimuthal signal and the time history of the displacement, the curves of mobility at the driving point versus frequencies could be plotted (see Fig. 15). Using these curves the dynamic instability analysis and two instability regions could be found.

In order to avoid instability in higher frequency region (the rolling mode) we increased the roll frequency by means of increasing the size of wheels, decreasing the pressure in the oleo-pneumatic shock-absorber.

For elimination of the lower frequency instability region (the side shifting mode) we matched the oleo hole in the oleo-pneumatic shock-absorber and added a floating piston in it to increase the damping.

All fundamental parameters of the main components were examined in dynamic test, for example, in longitudinal and lateral directions the static and dynamic stiffnesses and damping of wheels in various compressions, the stiffness and damping of the oleo-pneumatic ahock-absorber, the damping moment of the damper, the inertia moments of the body, etc.

Finally we examined it at ground running with artificial interferences and proved the Yan'an 2 helicopter was free of ground resonance.

3.2 Torsional Resonance in Transmission System

The rotating components such as crankshaft, fan, gears, rotors and shafts constitute a torsional dynamic system, on which the alternate torsion moments from engine, main rotor and tail rotor are acted.

In the field the following work was completed. There were the analysis of the natural torsional frequencies, stress measurment in ground and flight tests, sophistication of the main drive coupling design and fatigue tests.

An analytical model is shown in Fig. 16. Due to the in-plane flexibility of the main rotor blades the portion out of drag hinge was considered as a non-uniform elastic rotating beam. The other parts of the rotating system were considered as a multiplex shaft-disk torsional vibration system.

In order to determine the natural frequencies of this coupled system we used displacement impedance method. The matching point was selected at the drag hinge. The resulting diagram of the natural frequencies of torsional vibration system is shown in Fig. 17.

Based on theoretical analysis it is difficult to evaluate the alternate shear stress in the shaft of the transmission system due to torsional vibration. Therefore, we measures the actual stress and according to the spectrum analysis of the measured shear stress the torsional resonance frequencies could be determined. The straingages were bonded on main rotor shaft, main drive coupling, tail rotor shaft and main rotor blade spar. The stress signals were transmitted through the slip ring and recorded on a tape recorder.

According to the results of analysis and stress measurement the design of main drive coupling was sophisticated. The torsional stiffness of the original one was 3760 kgm/rad, and there was a peak at 74.3 HZ. The alternate shear stress was 610 kg/cm^2. When six rubber snubbers were added in the coupling, the torsional stiffness was reduced to 2580 kgm/rad, and the alternate shear stress was down to 250 kg/cm^2. At the operating speeds the peak of the alternate shear stress disappeared. This coupling was used in flight tests.

The fatigue test on the main drive coupling was completed (see Fig. 18).

In flight tests the alternate shear stress on main rotor shaft and tail rotor shaft were measured in hovering, climbing, level flight with maximum speed and flare.

All tests were performed perfectly.

Other works on dynamic problems had been done. For example, there were the analysis of the control system effect on natural torsional frequencies of rotor blade, the prediction of natural frequencies of tail rotor under the support of elastic fuselage, the application of mechnical impedance method to determinate the natural frequencies of rotor-fuselage combined system, etc.

4. GROUND AND FLIGHT TESTING

With the development program three prototypes were produced.

4.1 Rrototype 01 was used for static tests. It was an assembly of only the basic structure without the engine, real gear boxes and real rotors (Fig. 19). Using prototype 01 the following tests were completed. There were the static test of control system, static tests of basic fuselage structure at the condition of tie-down, maxium load factor, landing with single wheel, landing with main wheels, etc. These tests ensured the static strength of Yan'an 2.

4.2 Prototype 02 was built for the ground test (Fig. 20). It was damaged by ground resonance in Oct. 1967. After repairing the prototype 02 was used for impedance testing. We used two exciting methods and obtained satisfactory results. At the end of 1969 the ground resonance had been solved. Using the prototype 02 the natural frequencies of the basic structure were determined, the torsional vibration in transmission system was identified, the stress in main rotor shaft, main drive coupling, tail rotor shaft and blades of the main and tail rotors were measured, and the main rotor flutter test was completed. At testing stage prototype 02 ran on ground test for 100 hours to examinate the system relibility preliminarily.

4.3 Prototype 03 was used for flight test (Fig. 21). In May 1975 the program of actual flight test started. Military pilots tested the first self-designed light helicopter. This flight was a preliminary test. It aimed to determine whether the flight quality was satisfactory, the systems could work reliably and the stress on the main components were normal. As it should be the contents of the test program were conservative.

According to the pilot's reports the flight quality proved to be satisfactory. The pilots took only a short time to master it. Test pilots evaluated it: "In hovering and forward flight the stability and control of the Yan'an 2 are satisfactory, the helicopter is small and maneuverable, at the wind testing up to 45 km/h in hovering, turn-on-the-spot, maneuver at low altitude it completed without any difficult, that is obviously better than helicopter Z-5." "At climb, level flight, descent, right and left turn and flare the helicopter was stable and well followed with control. All of the systems operated are excellent."

In the initial stage of flight tests pilots felt that the yaw control was too sensitive. The transmission ratio of yaw control had been reduced from 1.54°/cm to 1.2°/cm. The yaw controllability became satisfactory.

4.4 Stress Level and Vibration

In the typical regions the stress and vibration were measured. The maximum alternate stress shown up at flare. The alternate shear stress at the main rotor shaft was 2.10 kg/mm², the alternate normal stress at the main gear box bars was 5.25 kg/mm², at the cyclic control rod was 0.36 kg/mm², and at the collective control rod was 0.36 kg/mm² too.

The vertical vibration near the left pilot's seat was recorded. In hovering the maximum amplitude was 0.16 mm, in climb was 0.0825 mm, in level flight was 0.066 mm, in flare 0.50 mm had been recorded.

The maximum amplitude of lateral vibration was less than 0.066 mm.

The pilots believed that the small Yan'an 2 helicopter was maneuverable, stable in all regions of flight, easy to operate and special suitable for training and observation roles.

5. COUCLUSION

The success of the preliminary flight test of Yan'an 2 proves that the basic ability to design and develop a helicopter in China has been provided.

The ability is showed as follows: Firstly we completed the design from layout to details, completed the theoretical analysis and tests on aerodynamics, strength and vibration, completed the manufacture and adjustment of the whole helicopter and tested in flight and got the satisfactory evaluation from pilots; Secondly, when technical troubles were encountered, we could solve it theoretically and experimentally using advanced technology.

Further plan includes the research work to develop composite rotor, CAD program for preliminary design, autocontrol system and method to determine the fatigue load spectrum.

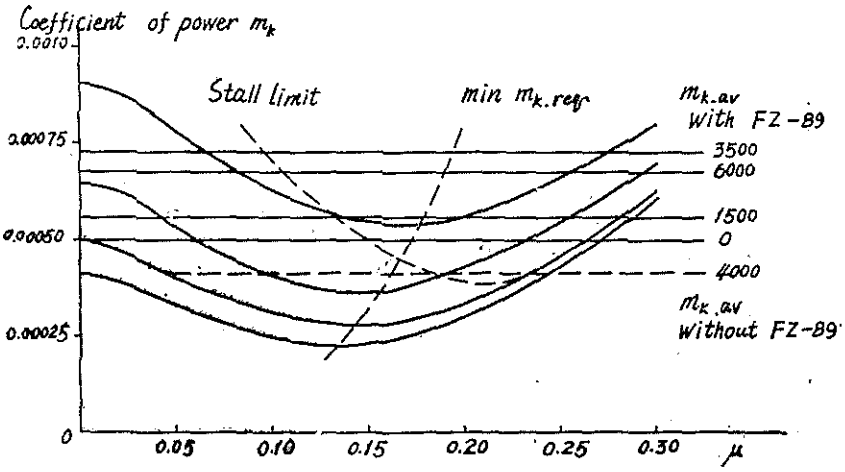


Fig. 2 Coefficient of Power Required Versus Speed

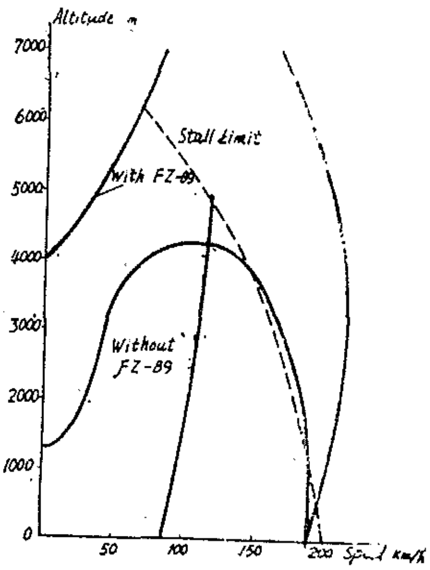


Fig. 3 Altitude Versus Speed

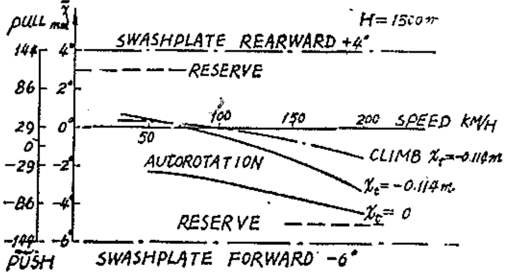


Fig. 4 Longitudinal Trim in Hovering and Forward Flight

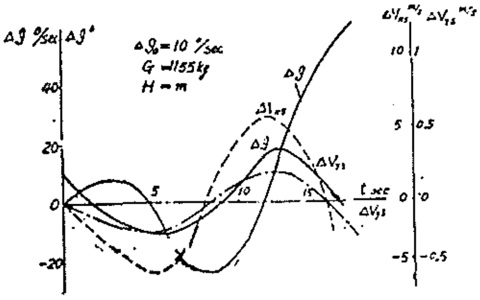


Fig. 5 Longitudinal Motion in Hovering

Fig. 6 Rotor Blade of Yan'an 2 and Small Blade for Rotor Tower

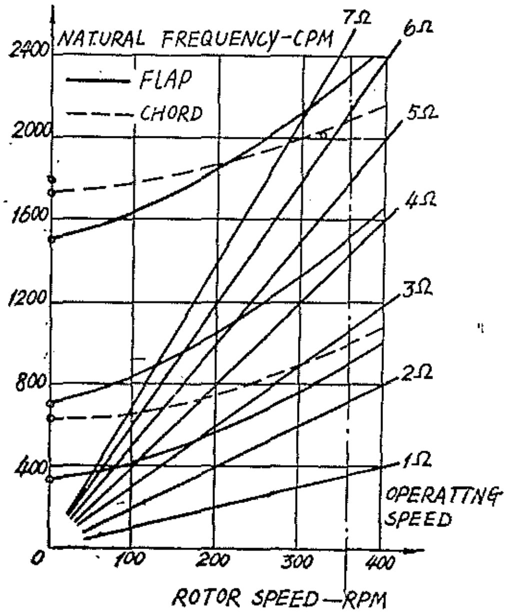


Fig. 7 Natural Frequencies of the Main Rotor Blade

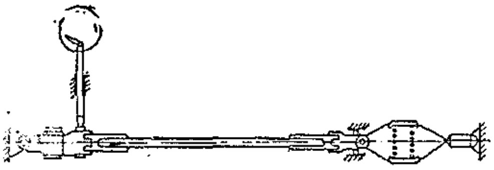


Fig. 8 Main Rotor Blade Fatigue Test Bench Schematical)

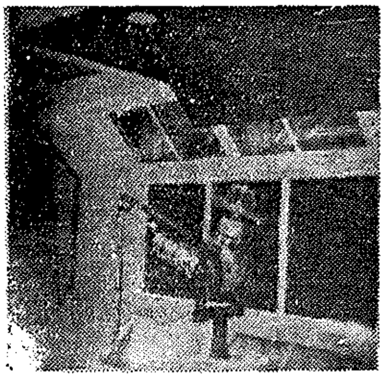


Fig. 9 Tail Rotor Test in Wind Tunnel

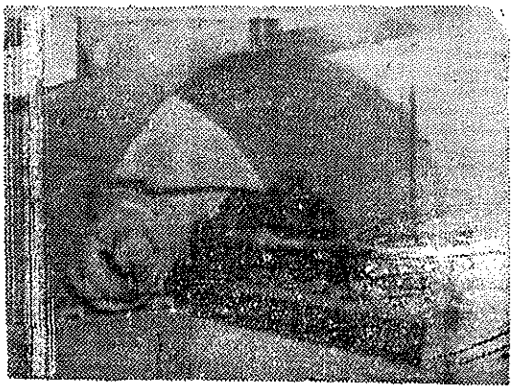


Fig. 10 Tail Rotor Driving Shaft in Fatigue Test Bench

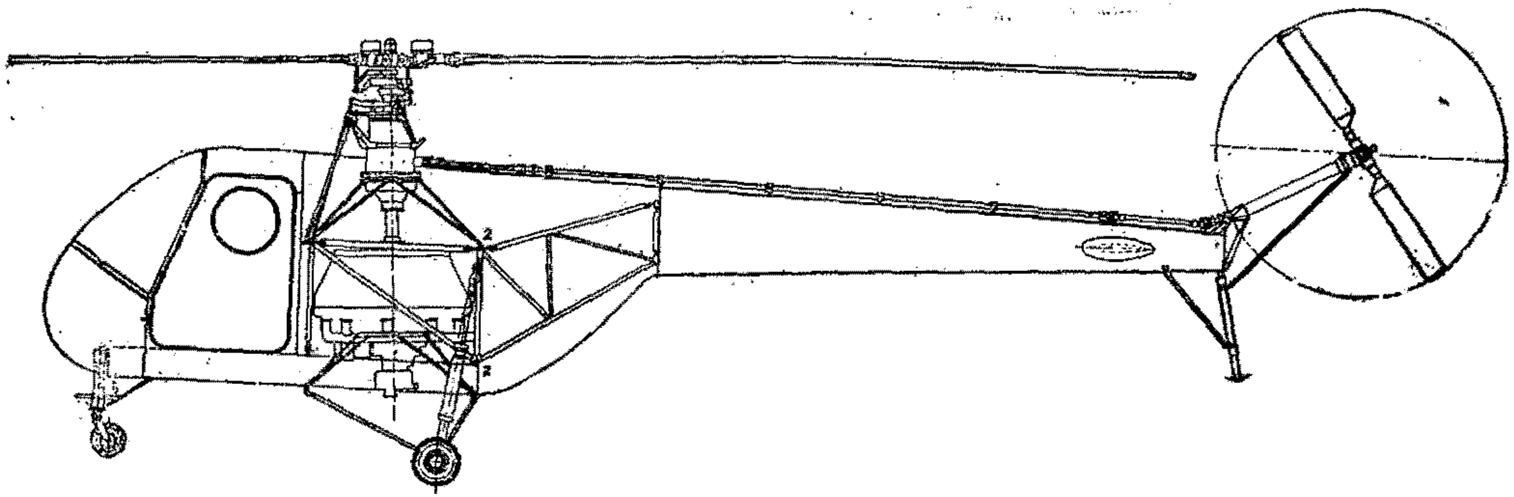


Fig. 11 Airframe

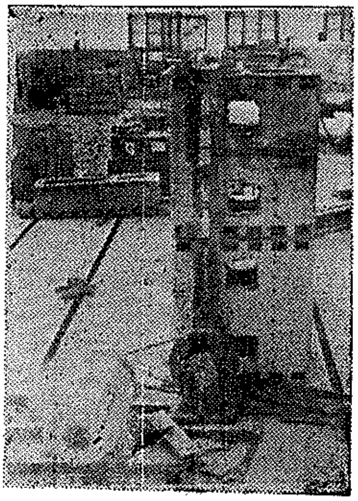


Fig. 12 Oleo Absorber in Test Bench

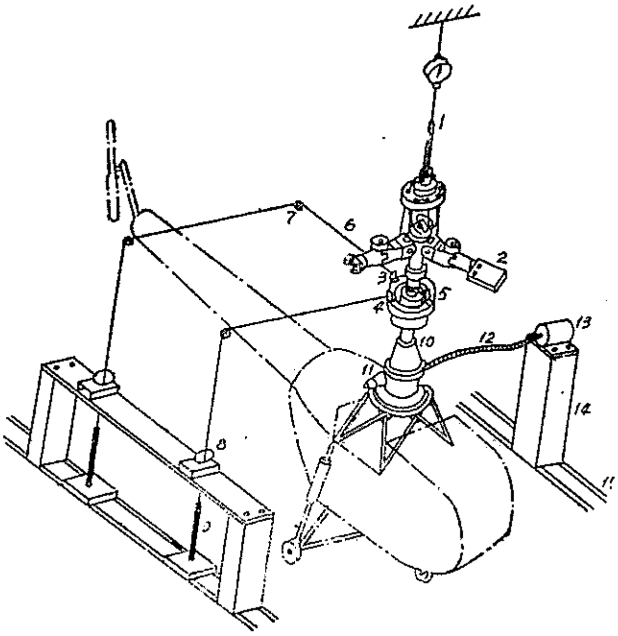


Fig. 13 Fuselage-landing Gear System Impedance Test Installation

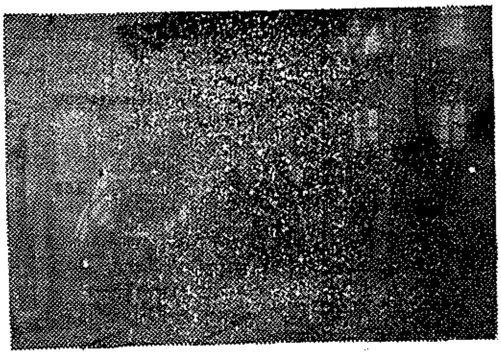


Fig. 14 Fuselage-landing Gear system Impedance Test

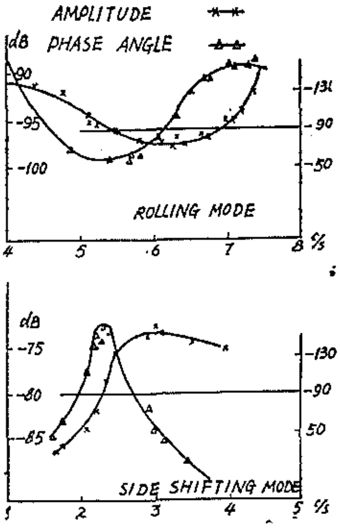
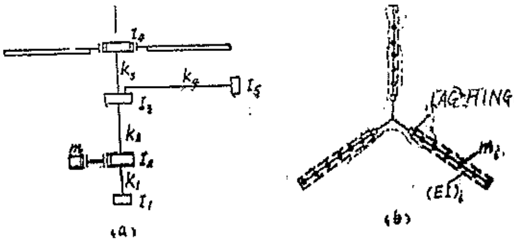


Fig. 15 Mobility Versus Frequencies



(a) (b)

Fig. 16 Analytical for Torsional Vibration

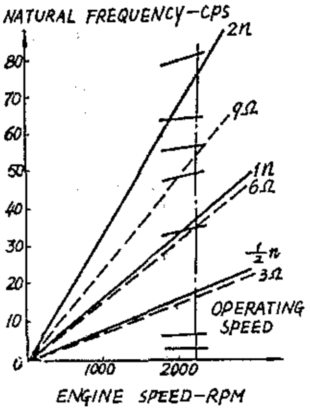


Fig. 17 Natural Frequencies of the Transmission System

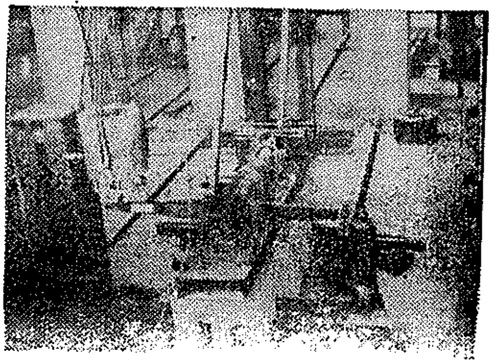


Fig. 18 Main Drive Coupling in Fatigue Test Bench

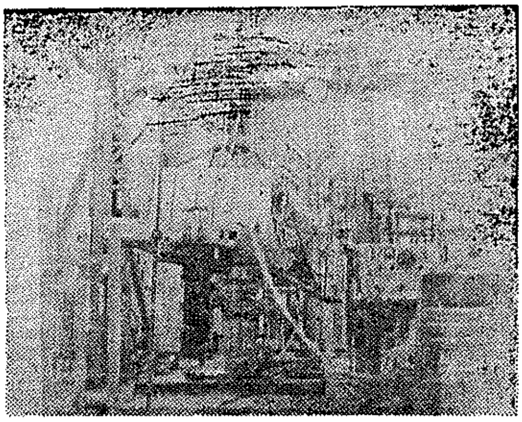


Fig. 19 Yan'an 2 in Static Test

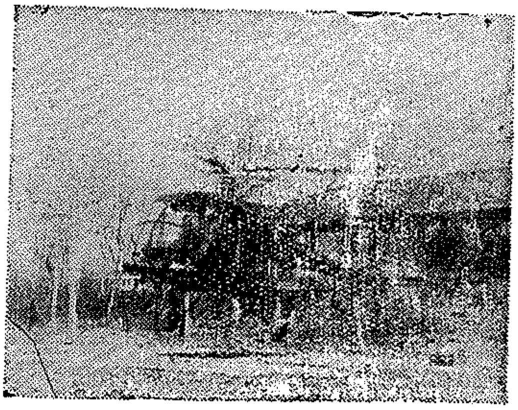


Fig. 20 Yan'an 2 in Ground Test

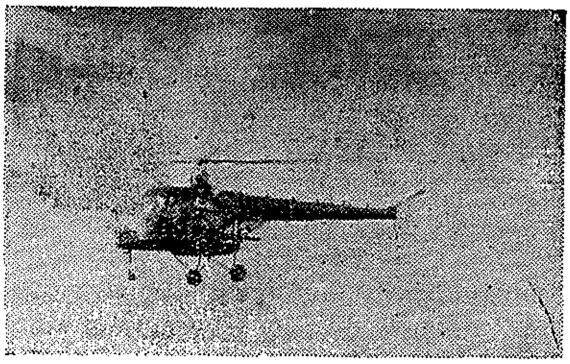


Fig. 21 Yan'an 2 in flight Test