Design Specifications for an Unmanned VTOL

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***Abstract* - Parametric technology based design specifications for a new unmanned Vertical Take-Off and Landing (VTOL) vehicle are presented. The design phase is followed by performance capabilities evaluation and crash / drop tests that determine VTOL strength and frame deformations. Drop tests performed have followed standard regulations used for airworthiness certification of such vehicles. Initial drop tests have dictated a frame re-design phase that has met set VTOL specifications. The Pro\Engineer specialized Computer Aided Design (CAD) software has been used throughout all phases and tests.**

Index Terms* - *UAV, VTOL, design, drop test.

I. INTRODUCTION

VTOL vehicles are a special class of unmanned aerial vehicles (UAVs) [1], designed and utilized for highly specialized missions due to their ability to land in difficult and restricted size areas (like a ship deck) and ability to hover over specific areas of interest, serving as ideal platforms for target inspection and identification. VTOLs, as well as UAVs, may be used in a wide variety of military, civilian and commercial applications. They are reusable, and they may be fully teleoperated, function autonomously or semi autonomously or following a combination of different operational modes. VTOLs have different payload capabilities and are equipped with custom-made sensor suites allowing them to complete specific tasks within a mission.

The main objective of this paper is to present design specifications of a new, currently under prototype development VTOL, for applications like target drone, automated surveillance, mapping, coastal inspection, border patrol, fire detection, etc. It is the outgrowth of our previous work presented in [2], in which a thorough comparison study and market analysis was conducted. Seventy-three different unmanned VTOLs (see Appendix A), manufactured worldwide, were studied and compared. VTOL comparison was performed as a function of specific technologies used to design VTOL propulsion, engines, and performance capabilities (payload, maximum speed, ceiling, endurance, range of flight). Flying performance limitations were also identified, providing helpful information considered in the proposed design.

Based on the comparison study [2] and the application domains, the following design parameters have been chosen: low cost, high speed, high payload, and flight time. Set specifications have been considered during the design phase and they have been compared with the values obtained by analytical calculations regarding VTOL performance.

In order to validate VTOL crashworthiness and safe operation, crash / drop tests have been performed. All tests have followed rules and regulations set by civil aviation authorities (such as the US FAA, NATO and the Civil Aviation Authority of Australia) established for the certification and airworthiness of aerial vehicles.

Tests have been implemented "virtually" with the aid of a finite element analysis (FEA) method. The tool was the Pro\Engineer specialized Computer Aided Design (CAD) software. The results were used to redesign the VTOL frame increasing its safety factor and reducing its overall weight.

The rest of the paper is organized as follows: Section II presents the design, while Section III discusses performance characteristics. The fourth section includes crash / drop tests, and section V concludes the paper.

II. DESIGN

The shape of the proposed VTOL is shown in Fig. 1.

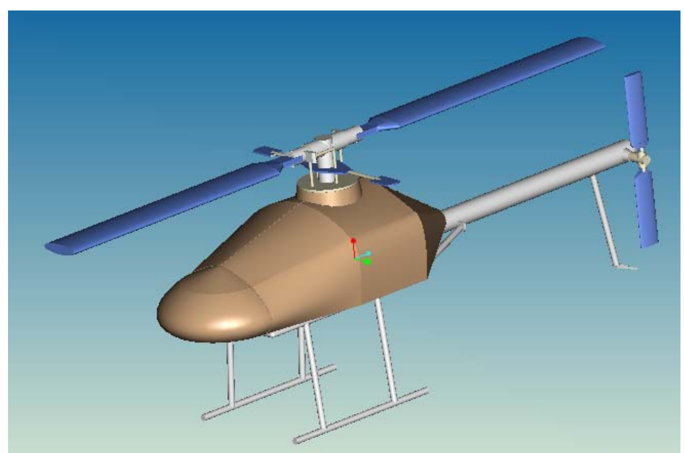

Figure 1. 3-D view of the VTOL

As shown in Fig. 1, a classic rotor system (with a main and tail rotor) is chosen for the VTOL propulsion, setting initial design limits for its shape, main frame design and placement of the rest of the components relative to the frame as shown in Fig. 2. Figure 2 illustrates the frame (1), the transmission (2), the main rotor (3), the engine (4), the fuel tanks (5) and the tail rotor (6). Each component is analysed next.

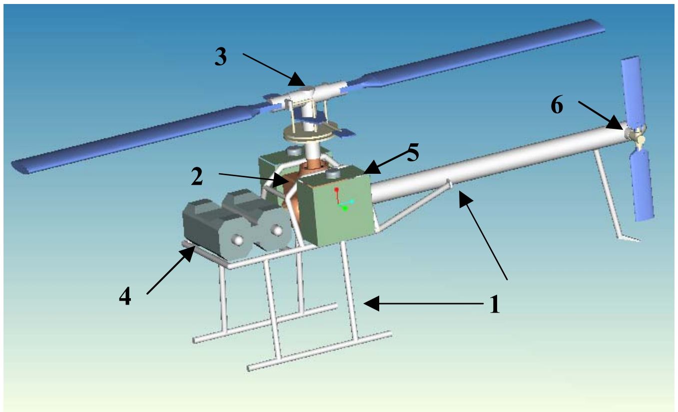

Figure 2. VTOL components

A. *Main and Tale Frame*

The VTOL frame or chassis consists of two parts as shown in Fig. 3, the main and the tail frame. These parts are joined together by four bolts at the backside of the main frame. This is the most important element of the vehicle design, since it dictates the vehicle's shape and must withstand loads applied during flight, take-off and landing. The material chosen for the frame is a *steel alloy*, because of its high strength and low price.

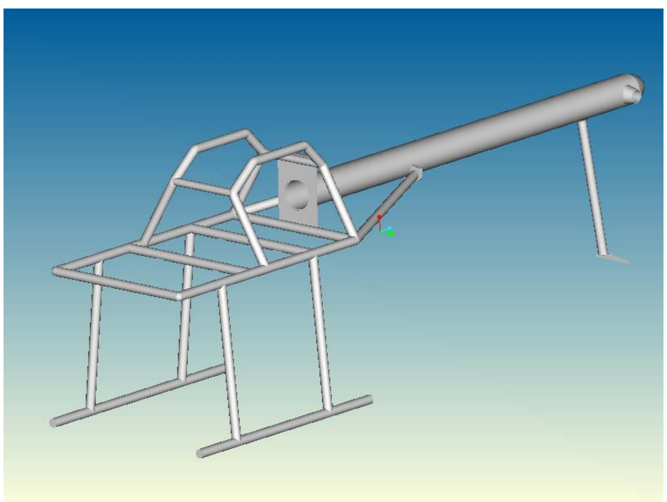

Figure 3. VTOL main and tail frame

B. *Transmission*

The transmission is placed at the center and back of the main frame. It transfers needed power from the engine to the main and tail rotors with a constant gear ratio. In case of engine failure rotors are disengaged so that the vehicle may land using autorotation.

C. *Main Rotor*

The main rotor is placed exactly above the transmission. It consists of two rotating blades with a total diameter of 3.23m. Using just two blades results in low cost, low weight and simpler construction, compared to rotors with three or more blades [3]. The blades follow the *23012 NACA series*, which is an asymmetrical airfoil.

D. *Tail Rotor*

The tail rotor is placed at the end of the tail frame; a rotating shaft passing through the tail boom transfers the movement to it. It has also two rotating blades with a total diameter of 67cm. The diameter depends on the main rotor diameter [3] needed to produce needed propulsion that will prevent the vehicle rotation around its vertical axis. The blades follow the *64212 NACA series*.

E. *Engine*

The engine is placed in the front of the vehicle. The main frame dimensions are set in such a way to allow for and accommodate several engine types with different horsepower depending on applications. Given the application domain, a two-stroke piston engine has been is chosen with 50HP horsepower and a weight of 21Kg.

F. *Fuel Tanks*

Two fuel tanks are placed in each of the two sides of the transmission. Fuel is transferred simultaneously from both tanks to the engine. Thus, the loss of weight due to fuel consumption is distributed equally keeping at all times the same balance and preventing stability loss during flight. Every tank has a capacity of 19.2 lt.

G. *Center of Gravity (COG)*

The position of the VTOL center of gravity is crucial for flying. The type of propulsion used is an important factor of defining the best COG position. In the proposed design, the ideal placement is exactly on the axis of rotation of the main rotor [3]. In this way, the frame remains horizontal during hovering; controlling and maneuvering the vehicle becomes easier.

In essence, VTOL component placement on the main and tail frame has been carefully chosen to result in the COG being a little in front of the main rotor axis.

H. *Electronic Equipment*

The electronic systems that will be placed on the vehicle consist of an altimeter, a GPS, a communication system, a gyro and a remote/autonomous control module. Depending on the mission and application such equipment may be modified.

III. Performance Characteristics

The design phase is followed by evaluation of the VTOL capabilities in terms of: weight capability during hovering, maximum speed, ceiling and endurance. The most critical parameters affecting such capabilities are available engine power, maximum weight, the rotors design and special aerodynamic factors [4-6].

Results are reported below.

A. *Weight Capability in Hover*

The VTOL altitude can alter the weight the vehicle may hold while hovering above a specified ground point. If the VTOL is positioned close to the ground, less power is needed for hovering; this state is called *In Ground Effect* (IGE). If the vehicle is hovering far away from the ground, more power is required; this state is called *Out of Ground Effect* (OGE). Figure 4 presents a graph of power versus weight, during IGE and OGE. From Fig. 4, it is shown that the proposed VTOL can hover with a maximum weight of 262Kg (245Kg) at IGE (OGE), respectively.

B. Forward Speed

In order to calculate the VTOL maximum forward speed, a graph of the available power versus speed is drawn as shown in Fig. 5. The curve shown corresponds to power needed to move the main and tail rotors so that the vehicle can fly forward with a specific speed. Calculations have considered factors related to aerodynamic drag losses due to the shape of the vehicle and the rotor blades, and power losses for secondary systems. Since the engine's power is 50HP, the maximum forward speed is calculated to be 194 Km/hr. Optimum speed may be estimated too, being the speed requiring the least power. Optimum speed is 98 Km/hr.

C. Ceiling

The ceiling is the maximum altitude in which the climb speed reduces to 0.5m/sec. The ceiling for this VTOL was found to be 4900m with maximum take-off weight. Firstly, the power needed for climb at the specified speed is calculated and the minimum power needed for horizontal movement of the vehicle is added. The total needed power is then compared to the available power of the engine, for different altitudes and total weight. From the diagram created (Fig. 6), the ceiling of the vehicle is calculated. It must be mentioned that the minimum power needed for horizontal movement of the vehicle is the power at the optimum speed, as stated at the previous paragraph.

D. Endurance

The VTOL's endurance corresponds to its flying time. According to the capacity of the fuel tanks (38.4lt) and the fuel consumption of the selected engine, it is found that the total time the vehicle can fly is 3.2 hours.

It is concluded that the values obtained are totally satisfactory and meet set requirements defined after the market analysis [2]. The capabilities of this vehicle are summarized in Table I.

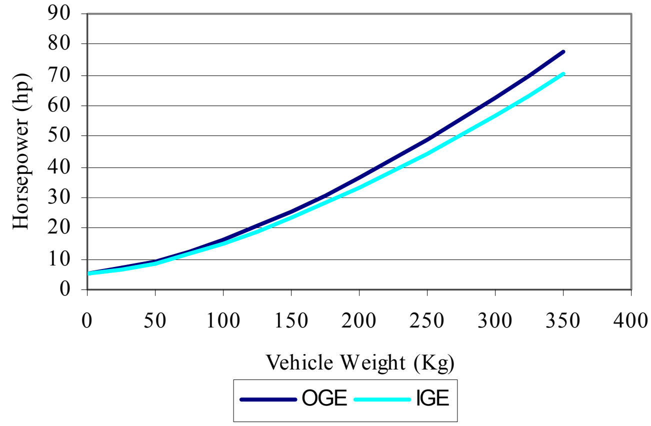

Figure 4. Horsepower versus weight for hovering in IGE and OGE

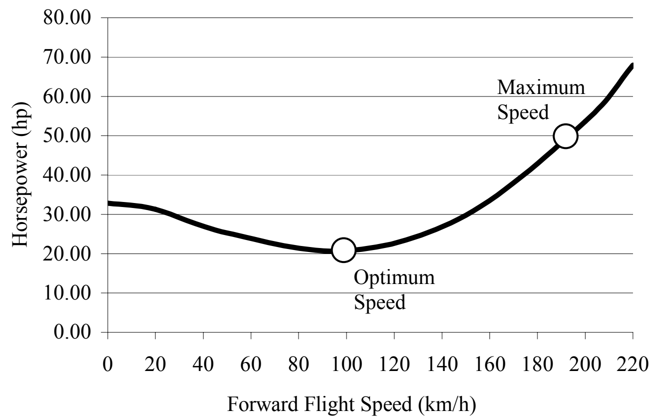

Figure 5. Needed engine power versus forward VTOL speed.

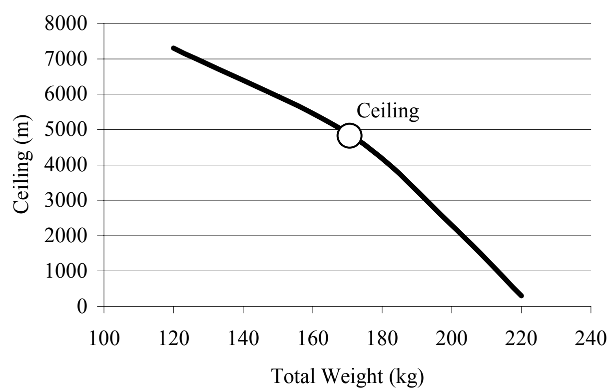

Figure 6. Ceiling versus total weight of the vehicle.

TABLE I
VEHICLE PERFORMANCE CHARACTERISTICS

Maximum Take-Off Weight	170 Kg
Payload	50 Kg
Maximum Forward Speed	194 Km/h
Ceiling	4900 m
Endurance	3.2 hr
Engine	Two-stroke, piston, 50HP
Length	2.75 m
Height	1.23 m
Main Rotor Diameter	3.2 m

IV. EVALUATION OF THE VEHICLE CRASHWORTHINESS

Loads a VTOL must withstand during operation are crucial for its lifetime. It is really important to validate whether a designed vehicle can operate safely by eliminating the possibility of material failures during flight.

The vehicle frame is the main component that needs be evaluated, being the component that must not fail as long as the vehicle operates within its limits. To evaluate the frame crashworthiness, several test under different operational conditions have been performed. These conditions meet rules and regulations set by civil aviation authorities about VTOL construction, maintenance and operation [7-10]. Specifically, virtual drop tests of the frame have been conducted from a height of 33cm above the ground and the stresses have been checked and calculated. If stresses overcome the material yield stress limit, plastic deformations occur and the frame is not satisfactory for this construction.

To estimate stresses developed, the ANSYS specialized FEA program has been used [11]. The drop tests have been simulated by using dynamic analysis features. Once the geometry model has been created, the lines, surfaces and solids can be meshed (discretized) to create the beam, shell or solid elements. The type of elements used, depend on the type of the problem to be solved and on the design of the structure. Thus, in this case, the mesh of the model (Fig. 7), consists of shell elements with different thickness that can simulate satisfactory the structure. The type of material is a linear isotropic model, simulating the 300M Steel Alloy used. The parameters of the material [12], are: Poisson's ratio: 0.27, Elastic Modulus: 199 GPa, Density: 7833 Kg/m^3, Yield Stress: 1517 MPa, Ultimate Tensile Stress: 1862 MPa. The total weigh of the frame is 44Kg and in order to model the 170Kg of maximum take-off weight, additional masses where put in specific locations of the frame, modeling the weights of the vehicle components. A series of drop tests have been performed, resulting in redesign of the frame so that an optimization of its weight and stress distribution occurs [13].

The first design of the frame, from which throw iterative evaluation and redesign we ended up to the frame presented, is shown in Fig. 8. This frame was modeled with an aluminum alloy of series 2014-T6. This material was picked because of its low weight, resulting at a frame weight of just 32Kg.

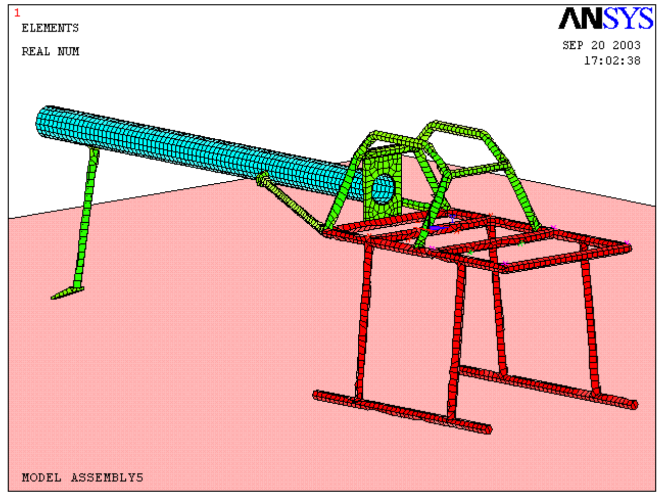

Figure 7. Meshed model of the frame.

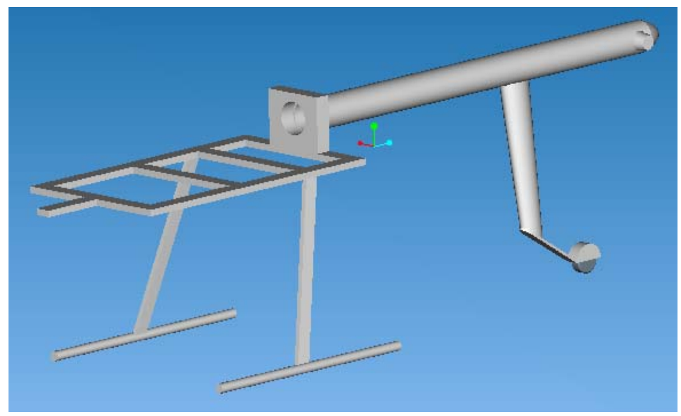

Figure 8. The first design of the main and tail frame of the vehicle.

The parameters of the material [14], are: Poisson's ratio: 0.33, Elastic Modulus: 72.4 GPa, Density: 2800 Kg/m^3, Yield Stress: 414 MPa, Ultimate Tensile Stress: 483 MPa. However, the results obtained from the crash tests didn't show a satisfying reaction of the frame, mainly because of large deformations of the front part.

A. Results

The first results obtained via FEA, were for the first design of the frame. As stated before, big vibrations and deformations in the front part where reported, indicating an unstable base for the engine of the vehicle. Also, it was found that the material used, didn't have the strength to hold a vehicle of this weight through a crash test. The material yield strength was proven lower than the stresses found, thus this design didn't qualify the evaluation. Specifically, the drop test was conducted for 80msec and the time needed for the calculations was 12 hours. The value of maximum stress reported, it is presented in the graph of Fig. 12. This graph represents the value of stresses reported in a specific area of the frame (circled), where the frame is connected with the skids. The stresses are given versus the time of the drop test. It is shown that at this point the stresses overcome the yield stress limit (dotted line).

After iterative redesign and testing steps, satisfactory results were obtained for the final frame. The final drop test results are presented here for verification. The drop test was conducted for a period of 60msec after the impact. The time needed for the calculations was almost 8 hours. Figures 9 through 11 present plots of the stresses developed in different time steps of 7, 10 and 20msec after impact. At the bottom of every picture a color contour is used to indicate their values. It is shown that the maximum stress found was 1280 MPa at time of 10ms, sufficiently lower than the material yield stress. So, the frame can withstand loads without presenting any plastic deformation, verifying the proposed design and that the frame can guarantee the safe operation of the vehicle.

In order to have a better aspect of the stresses developed in the most critical areas of the frame, graphs of stress versus time are presented. Figure 13 presents the specified areas of interest (circled). It can be seen that at the point the bars connect the skids to the rest of the frame, high stresses occur but below the yield stress limit (dotted line). The maximum stress is reported at the middle of the frame where the payload of the vehicle is mount. Nevertheless no problem occurs since again the material yield stress is bigger.

V. Conclusions

The main objective of this paper has been the presentation of a new VTOL UAV, designed to cover a wide range of scientific and commercial applications.

Analytical calculations have been followed to estimate the capabilities and performance characteristics of the proposed vehicle. Utilizing specialized FEA software, drop tests have been conducted, resulting in verification of design specifications and VTOL operation with no indication of material failure. Results have shown that this new vehicle may be an ideal platform for almost any kind of applications.

Acknowledgment

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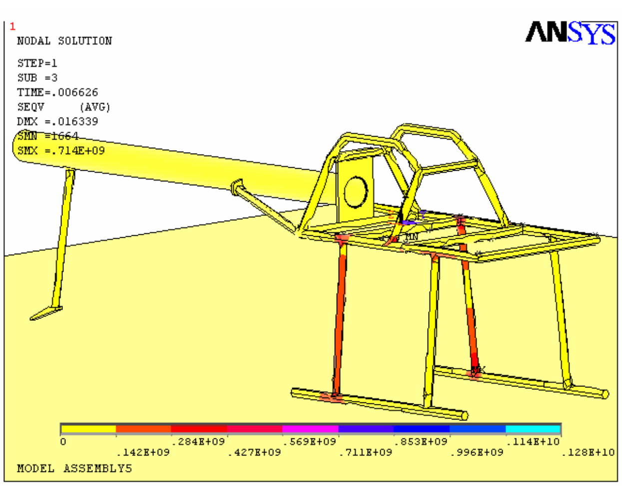

Figure 9. Representation of stresses at 7msec of the drop test.

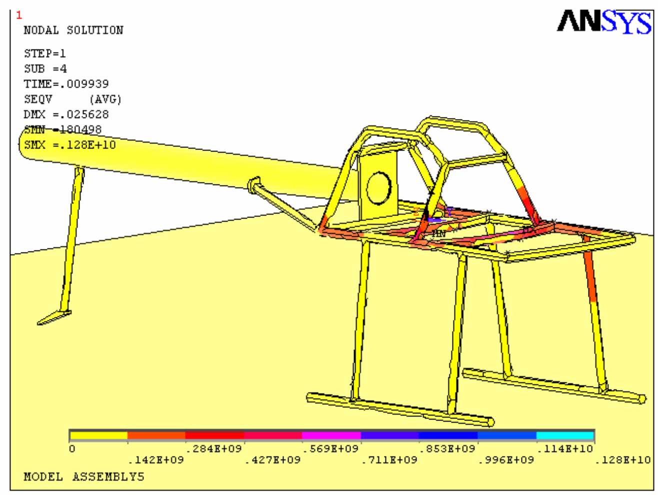

Figure 10. Representation of stresses at 10msec of the drop test.

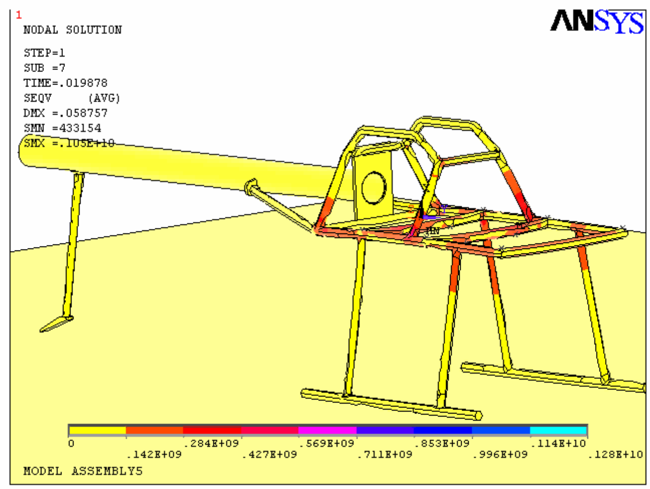

Figure 11. Representation of stresses at 20msec of the drop test

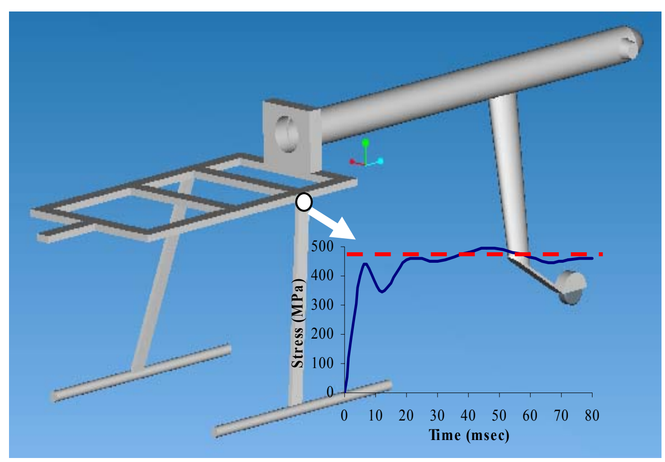

Figure 12. The maximum stresses developed versus time in the first design of the frame.

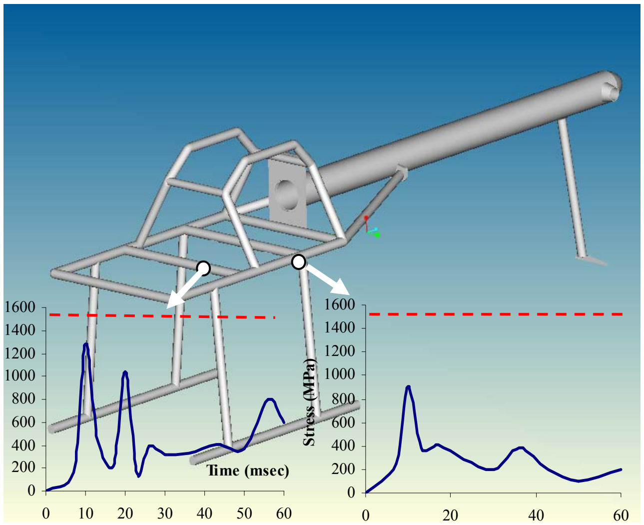

Figure 13. The maximum stresses developed versus time in the final design of the frame.

APPENDIX A

	Model Name	Manufacturer
1	ACRW	BOSTAN RESEARCH INC.
2	Aerobot	MOLLER
3	Aerohawk	AERONAUTICS UAV SYSTEMS LTD
4	23F	AEROCAM
5	60F	AEROCAM
6	Apid Mk4	SCANDICRAFT SYSTEMS
7	Apid Mk4-X	SCANDICRAFT SYSTEMS
8	Apid Mk-6	SCANDICRAFT SYSTEMS
9	Arch 50	DAEWOO HEAVY INDUSTRY
10	Argus	SCHWEIZER
11	Camcopter	SCHIEBEL
12	CL-227 Sentinel	BOMBARDIER AEROSPACE
13	CL-327 Guardian	BOMBARDIER AEROSPACE
14	CL-427 Puma	BOMBARDIER AEROSPACE
15	Cycloprop	BOSCH AEROSPACE
16	Cypher	SIKORSKY
17	Cypher II	SIKORSKY
18	CVG 2002	COPTERVISION
19	D'HovRBot	D-STAR ENGINEERING
20	DP-4	DRAGONFLY PICTURES Inc.
21	Dragonfly	BOEING - DARPA
22	Dragonwing	BOEING
23	Eagle Eye	BELL
24	FLYRT	NAVAL RESEARCH LABORATORY
25	HELI 25	B.T.A. AUTOMATIC PILOTING INTERNATIONAL
26	Helicam	MLB CO.
27	Heliot	CAC SYSTEMS DRAGON FLY
28	Heliwing	BOEING CO.
29	Heliplane	CARTERCOPTER
30	Hetel Light	ECT INDUSTRIE
31	Hetel Standard	ECT INDUSTRIE
32	Hetel Large	ECT INDUSTRIE
33	High Point	NAVAL RESEARCH LABORATORY
34	Hummingbird	MOLLER INTERNATIONAL
35	Hummingbird	NAVAL SURFACE WARFARE CENTER
36	Hummingbird A115	FRONTIER SYSTEMS
37	Hummingbird A160	FRONTIER SYSTEMS
38	Hovtol	JOHNNY SWINSON
39	iFF-4	IMAR GMBH
40	Istar 29	MICRO CRAFT
41	JAG	VICTORY SYSTEMS
42	Ka-37	KAMOV
43	Ka-137	KAMOV
44	K-Max Burro	KAMAN
45	Manta	FREEWING AERIAL ROBOTICS CORP.
46	Maple Seed	MLB CO.
47	MiniCypher	SIKORSKY
48	Nitro Hawk	CHANNON AIS
49	Pidgeon	ARMY RESEARCH LAB
50	Project Elliott	ORION AVIATION
51	QH-50 Dash	GYRODYNE
52	Rmax	YAMAHA
53	R-50	YAMAHA
54	RoboCopter	KAWADA
55	Rogue	REMOTE INTELLIGENCE SYSTEMS, Inc.
56	RPG Midget Mk III	TECHMENT AB
57	RPH-2	FUJI HEAVY INDUSTRIES
58	RQ-8 FireScout	NORTHROP GRUMMAN
59	Scorpion Model 100	FREEWING AERIAL ROBOTICS CORP.
60	Scorpion Model 60	FREEWING AERIAL ROBOTICS CORP.
61	Sea Bat	ORION AVIATION
62	Sea Spray	PIASECKI AIRCRAFT CORP.
63	Seamos	EADS – DORNIER GMBH
64	Sender	NAVAL RESEARCH LABORATORY
65	Sky Robot	HUMMINGBIRD AVIATION, INC.
66	Spin Wing	THORPE SEEOP
67	SPRITE	AEROBOTICS
68	SteadiCopter	STEADICOPTER
69	VerticalStar	LOCKHEED MARTIN
70	Vigilant F2000	TECHNOSUD – THOMPSON-CSF
71	Vigilante 496	SAIC
72	Vigilante 502	SAIC
73	WZ-1	NANJING UNIVERSITY OF AERONAUTICS AND ASTRONAUTICS

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