Mechanical Instability

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Tomasz Krysinski
François Malburet

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Foreword

In a previous work, *Mechanical vibrations - Origin and control*, published in 2003, Tomasz Krysinski, Dynamics Specialist, former Head of the Vibration and Internal Noise Department at Eurocopter Engineering and Design Department, and François Malburet, Teacher-Researcher at the Ecole nationale supérieure d'arts et métiers of Aix-en-Provence, analyze the forced response of deformable mechanical systems subjected to periodic vibratory forces as well as to the dynamic optimization methods, and active and passive antivibration devices designed to limit the related effects.

In this work, which supplements the preceding one, the same authors are interested in the stability of mechanical systems, that is in their free response when they are moved away from their equilibrium position subsequent to a disturbance.

After a brief reminder of the main methods of analysis of the dynamic stability of systems, the authors highlight the fundamental difference in kind between the forced vibration resonance phenomena of mechanical systems subjected to an imposed excitation, and the instability phenomena which characterize their free response. If both types of phenomenon may lead to great deformation amplitudes and fatigue damage to the structure, the unstable phenomena are potentially much more hazardous since they may lead to sudden destruction of the structure in the event of divergent oscillations.

Sometimes also, unstable dissipative systems are subjected to self-sustained oscillations initially divergent but which saturate due to system behavior nonlinearities, thus resulting in a periodic permanent rating termed limit cycle. This is probably why the resonance phenomena and instabilities are sometimes mistaken for each other although the relevant analysis methods and mechanisms are very different, such as shown by the authors through the numerous examples presented.

The authors devote an entire chapter to the analysis of the phenomenon known as ground resonance of helicopters, which is in fact a potentially destructing self-sustaining instability resulting from coupling between the lag motion of the rotor blades and the motion of the aircraft standing on its landing gear.

Dynamic adaptation of the structure ensures the stability of the phenomenon by selecting the stiffness and damping characteristics for the landing gear, and lag adapters in order to correctly position the eigenfrequencies of the fuselage standing on its landing gear, and the blade lag eigenfrequency by preventing mode crossing within the normal rotor speed operating range while providing the damping necessary for the system stability (Coleman's criterion).

Active control of ground resonance (and air resonance) is then approached. It consists in controlling the fuselage roll oscillations, measured by means of accelerometers placed in the structure, through the rotor main servocontrols which directly act on the cyclic pitch and hence on the blade flapping response, and indirectly on the lag, through the inertial coupling induced by the Coriolis forces.

The next chapter is devoted to the stability of drive shafts of rotating machines, and especially to a form of instability which is expressed through appearance of self-sustained bending vibrations on nonsynchronous frequencies of the shaft rotational speed, and which often lead to a limit cycle resulting from saturation of the forces. The authors show that the energy which supplies the vibrations originates from an external source and, and that such instability is related to the presence of damping internal to the rotating system whereas the original external damping reduces the risk of instability.

The last chapter concerns the problems of stability which may result from the interaction of a fluid with a flexible structure whose deformations change the fluid flow. Such aeroelastic coupling may give rise to self-sustained oscillations whose amplitude increases upon every cycle until their divergence leads to failure of the structure. In other cases, a limit cycle will be reached when there is an energy equilibrium state characterized by oscillation amplitude such that the energy dissipated by the structure compensates for the external energy supply.

Such *flutter* phenomena concern a substantial number of structures subjected to the effect of wind, like engineering structures, bridges, buildings and electric line cables, airplane wings or else helicopter blades and several cases which are approached in that chapter.

Whirl flutter of the rotors of tilting rotor convertible craft is the subject of a special study which details the relevant mechanisms and shows the effect of all system characteristics on the critical speed at which instability occurs.

We obviously recommend reading of this work, fruit of the collaboration between an industrial engineer and a university teacher, to all people who wish to deepen their knowledge as regards rotary wing dynamics.

Philippe ROESCH
VP Technology & Product Innovation
Eurocopter

Preface

The unstable behavior of structures has always constituted a substantial concern for designers. A simplified definition would consist in saying that the equilibrium of a dynamic system is stable when it remains close to its equilibrium position after any disturbance. Conversely, the system is unstable when it tends to leave its equilibrium position after such a disturbance. This definition will be specified and extended in Chapter 1.

The unstable behavior of structures caused much destruction in several industrial sectors, whether in naval construction, mechanical construction, land construction or air construction. In this foreword, we propose several examples of damage caused by instabilities:

– *flutter* of airplane stabilizers;

– *whirl flutter* of rotors;

– ground resonance phenomenon leading to destruction of helicopters;

– instability caused by a hydrodynamic bearing, resulting in damage to a turbine;

– instability due to coupling between a governing system and the behavior of a rotating system.

Airplane Stabilizer Flutter

The aeroelastic coupling phenomenon occurring on airplane wings or stabilizers, termed *flutter*, caused many disasters.

The most recent example which was made public concerns the E-6A aircraft, Navy's version of the Boeing 707-320 airplane. In February 1989, that airplane lost the upper section of the tail fin and the rudder control surface in flight, Figure 1.

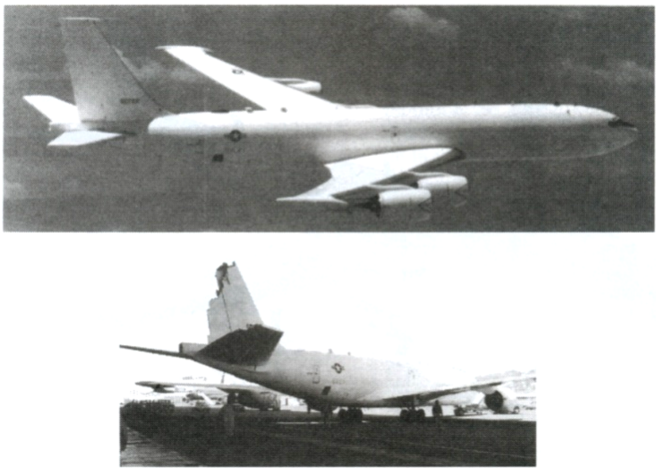


Figure 1. *Crash due to flutter on Boeing E-6A tail fin*

The problem was solved by rigidifying the tail fin by extending the spar up to the tail fin tip and reducing the hydraulic pressure in the rudder control surface.

These aeroelastic phenomena constitute, for the aeronautics manufacturers, and especially for the civil aircraft manufacturers, a concern from the design phase to certification, including flight tests [LAC 95]. This problem becomes increasingly crucial due to the emergence of flexible aircraft combining size increase and optimization of the structural index (ratio of the total weight to the empty weight).

Rotor Whirl Flutter

Whirl flutter concerns the aeroelastic coupling of a rotating system with blades or vanes in an airstream. The difficulty in controlling this phenomenon can be illustrated by a historical approach. It appeared on the first constructions of tiltrotor planes, it was hard to model and, consequently, very hard to predict on the first aircraft. The tiltrotor concept and the origin of *whirl flutter* are explained in Chapter 5.

The development of the first tiltrotor planes encountered, as from the beginning, dynamics problems extremely serious, which required more than 10 years of work to be solved, and therefore delayed accordingly the availability of the first operational and reliable tiltrotor plane. The first studies to produce a tiltrotor aircraft date back to the end of the 1940's and led, in a first time, to experimental machines capable of taking off but not of operating a complete conversion to the airplane mode.

On order from the US Army, Bell Helicopters was the first company to propose in 1955 an aircraft capable of flying, model XV-3. The initial version of that machine was equipped with three-blade hinged rotors. The first ground and flight tests revealed dynamics problems. Known as "rotor/pylon instability", these problems persisted for many years and resisted the attempts to analyze and understand.

The expression of this instability, encountered during the first hovering flight of the aircraft, was the appearance of an extremely high vertical vibration level at the cockpit which caused the pilot to land in an emergency.

Many changes were applied to the XV-3 aircraft in order to attempt to solve this problem, but with no significant success: increased rotor mast length, increased flight control component stiffness, modified mast damping and stiffness.

The vibrations persisting in flight led to add struts to the wing in order to increase its stiffness. This seemed to correct the problem. However, as from 70 knots, with the rotors in vertical position, instability reoccurred but remained low. The phenomenon was deemed minor and easily controllable; the project of rotor tilting was carried on. The consequences were catastrophic, with the appearance of violent vibrations which caused the crash and destruction of the aircraft.

Figure 2. *Bell XV-3 Helicopter with two-blade rotor*

The three-blade hinged rotor was then replaced with a two-blade semi rigid rotor which caused no instability, Figure 2. It should be noted that the struts designed to stiffen the wing were not removed.

Other dynamics problems however arose: rotor *weaving*, mast subharmonic oscillations. They were solved by increasing the stiffness of the rotor control systems and modifying the blade mass balancing, as well as by reducing the mast mass and rotor diameter. This required many tests on test benches.

Simultaneously with these changes, the first modeling operations run on a computer (in 1958!) begun. They led to better understanding of the physical phenomena involved. The aircraft then succeeded all conversion and reconversion phases to which it was subjected, but kept very bad flight qualities in airplane mode. Delivered to the NASA for testing purposes, new problems were detected: low longitudinal stability, excessive flapping during flight maneuvers, etc.

In 1962, after changes to the pitch-flap coupling, new wind-tunnel tests were performed, revealing a rotor described as "nervous", and mast oscillations at low frequency, the origin of which was inexplicable at that period.

So, for those first years of development, Bell succeeded in flying a tiltrotor aircraft in all of its flight configurations, but with low dynamic qualities and suffering from inexplicable main shaft/rotor instability. Those prohibitive faults seemed to definitely condemn the tiltrotor form whose development was provisionally put on the back burner.

At the same period, a Lockheed propeller aircraft crashed because of a problem of instability of the powerplant and identified later as being a *whirl flutter* phenomenon. After many efforts of analysis and modeling, the instabilities on tiltrotor aircraft were finally explained and identified as being *whirl flutter* equivalent to that of airplanes. There nature was however even more complex due to the special configuration of the rotors with flapping hinges. This theoretical success brought the idea of the tiltrotor aircraft back to the fore.

Many scale models (similarities of Lock, Froude, Froude-Mach) were then built and tested in wind tunnel with more or less success to validate the assumptions resulting from those studies. After much hesitation, the tests confirmed the ideas which resulted from the studies. The main conditions to have a rotor showing no *whirl flutter* were:

– high rotor mast stiffness,

– highly coupled mast and swashplate displacements,

– limited blade flapping.

In the same way, it was demonstrated that low wing stiffness and positive pitch-flap coupling were causes for instability (See Chapter 1). Wind-tunnel tests at low speeds confirmed all of these data. They had just to be validated by a high speed test on the full-size XV-3 model. All attempts to destabilize the rotors failed, but at the moment the test seemed to be a success, a very violent instability occurred which lasted three seconds and after which the two nacelles with their rotor were torn out and crossed the wind tunnel.

The crash analysis showed that this gyroscopic flutter-type resonance was due to a loss of stiffness in the nacelle/wing assembly caused by fatigue failure of the rivets which retained those components between each other. This was confirmed by testing under similar conditions on a scale model.

Figure 3. *BELL XV-15 tiltrotor aircraft*

Thus, that failure confirmed the necessity of having very great wing and mast stiffness in order to prevent occurrence of instabilities of the *whirl flutter* type. The continuation of the tiltrotor aircraft development was the contract placed in 1973 to Bell by the NASA and US Army in order to build an industrializable tiltrotor aircraft, XV-15, which in turn led to the V22 built by Bell and Boeing for the US Marine Corps, Figure 3. On those machines, the problem of *whirl flutter* was considered in the design, and the flight tests showed no expression of the phenomenon.

Ground Resonance on Helicopter

The ground resonance phenomenon on helicopters results from coupling between the modes of the rotor and airframe standing on its landing gear. It caused many crashes leading to destruction of prototypes or aircraft in service.

That phenomenon appeared during an experimentation program using a helicopter equipped with a rotor head with no lag damper and provided with interblade struts [LIB 98]. In order to test the effectiveness of that new rotor head, the test procedure consisted in regularly increasing the rotor speed while measuring the fuselage vibrations so as to check for any abnormal frequencies.

To perform that test, a Test Engineer sit down in the cockpit at the controls with the helicopter moored, cables not taut, the observer standing upright close to the helicopter at the rotor center of rotation in order to measure the vibration with a stopwatch. On the given signal, the Test Engineer opened the piston engine throttle. Entering resonance was sudden and unexpected. The displacement was so violent that the Engineer seat collapsed, thus preventing the Engineer from accessing the ignition control. He succeeded to shut down the engine only after prolonged efforts to counteract the force which pushed him rearward to the rotor.

Meanwhile, outside, the observer saw the helicopter suddenly swing in roll and the helicopter mooring cables be successively tautened and slackened.

During the investigation, blade debris of the vertical engine cooling fan was observed (fatigue failure due to sudden heading change and violent roll). Those pieces were ejected from the cowling over the observer head. One of the aluminum blades was cut at the hub and ejected like a javelin.

It should be remembered that the phenomenon is extremely violent, characterized by fast divergence leaving little possibility to the flight crew to react. This phenomenon shall be controlled upon design of the helicopter, with safety margins integrating the affecting parameters such as climatological conditions, landing conditions, parts wear, etc.

Instability of Rotating Systems Related to Hydrodynamic Bearings

At the beginning of the 1920s, when the General Electric Company knew problems of instability with some of their new turbocompressors developed for blast furnaces, the causes of rotor dynamic instability seemed to be mysterious.

Several years were necessary for the engineers to determine the causes. They also identified that the oil-film bearings of the shaft were a source of instability through a "whipping" phenomenon, Figure 4.

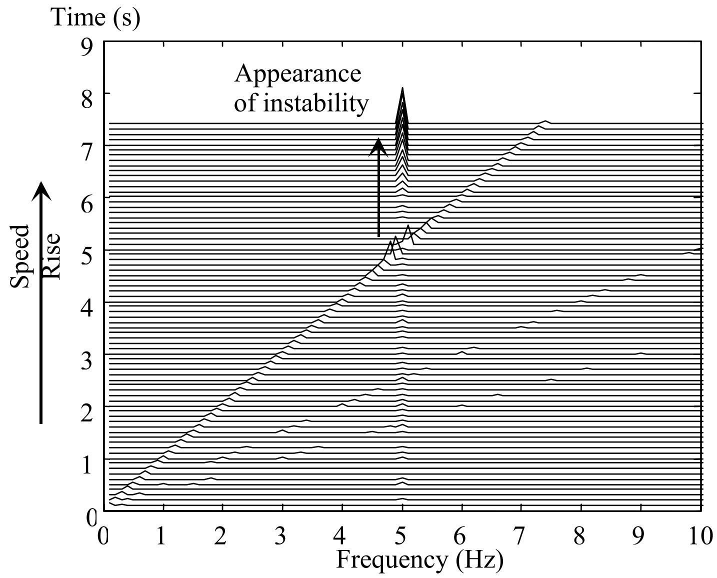


Figure 4. *Frequency spectrum upon starting of a rotating system. Measurement with accelerometer secured to casing. Instability appearance*

More recently, on high-speed turbomachines, designed to meet higher performance specifications, the instability problems appeared again. The most outstanding industrial example was the rotor dynamic instability encountered on the turbopumps of the space shuttle main engine [CHI 93, HER 92].

Such problematics is also encountered on more conventional systems, such as natural gas reinjection compressors, electric power plant turbines, and aircraft turboshaft engines and turbojet engines.

This type of behavior also appears in the case of gas bearings. In 1897, Kingsbury built and tested the first gas bearing. Air was used as a fluid to lift a shaft weighing 23 kg. The bearing had a diameter of 152.4 mm with a radial play of 0.203 mm and a length of 158.75 mm. The shaft with this gas bearing was fully lifted from 250 rpm. That experiment proved that air can be used as an interface for a rotating system. One hundred years later, gas bearings are used in many fields:

– turbomachines: pumps, fans, compressors, etc.;

– machine tools: drills, grinders, trolley guide systems;

– electric motors;

– textile machines;

– dental drills.

In order to displace two fluid layers, it is necessary to apply a force which must compensate for the fluid internal friction. This force (F) over a unit of surface area (A) defines the tangential stress:

$$\tau = \frac{F}{A} \tag{1}$$

According to the Newton's law, this stress is proportional to the speed gradient in the direction perpendicular to the stress action plane:

$$\tau = \mu \frac{\partial v}{\partial n} \tag{2}$$

Coefficient μ corresponds to the dynamic viscosity which, for gases, increases with temperature. For comparison, at an ambient temperature of 20°C, the air dynamic viscosity is 1/20,000th of that of oil, and 1/55th of that of water. As a matter of fact, the lift capability of gas bearings is much lower than that of oil bearings.

There are two types of gas bearing: non-supplied bearings and supplied bearings.

As regards non-supplied bearings, often termed dynamic bearings, the lift of the rotating component is obtained by increasing the pressure between two surfaces moving in relation to each other, as shown in Figure 5.

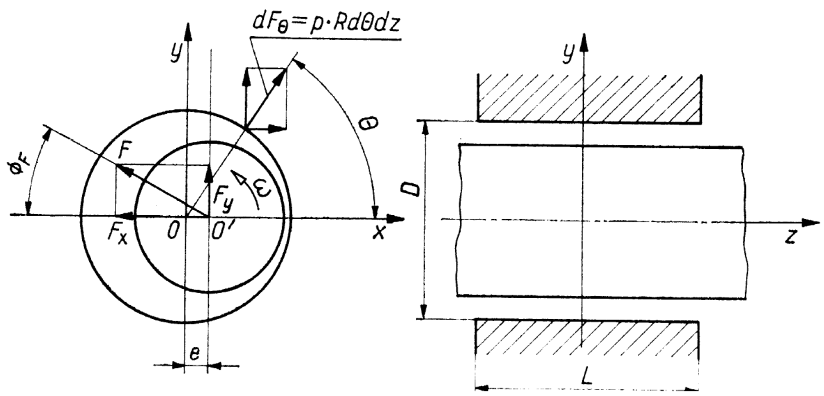


Figure 5. *Schematization of hydraulic bearings*

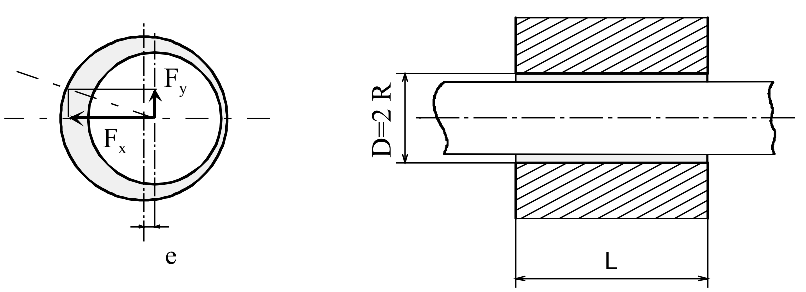


Figure 5. *(continued) Schematization of hydraulic bearings*

The lift capability of the bearing can be assessed by integrating the pressure onto the bearing surface area:

$$\begin{cases} F_x = \int_{-L/2}^{L/2} \int_0^{2\pi} p(\theta)\cos(\theta)\, R\, d\theta dz \\ F_y = \int_{-L/2}^{L/2} \int_0^{2\pi} p(\theta)\sin(\theta)\, R\, d\theta dz \end{cases} \qquad [3]$$

This pressure increase is caused by the shaft which displaces in the bearing.

As regards supplied bearings, the lift is given by superimposition of the dynamic effect and the static effect due to the gas pressure related to the external source (Figure 7).

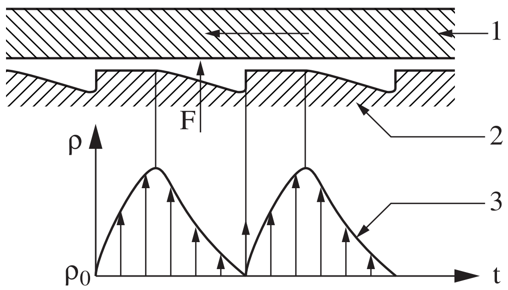


Figure 6. *Non-supplied bearing pressure field*

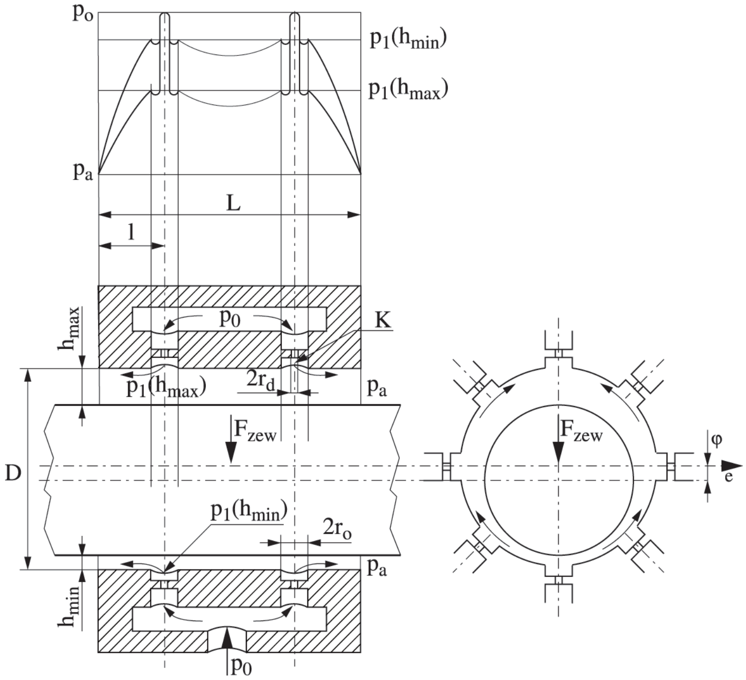


Figure 7. *Schematization of supplied bearings*

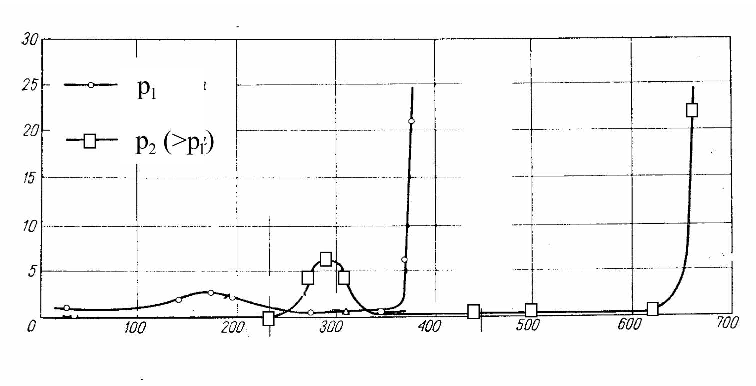
The amplitude of shaft motion in the bearing is given by Figure 8. This figure has been drawn for two supply pressures; two operating areas can be observed:

a) the amplitude increase in part 1 is caused by the conventional phenomenon of passage through resonance by an unbalanced rotor. Stiffness and damping are caused by the gas film which separates the bearing shaft;

b) the amplitude increase is very violent (part 2) and results in the shaft stopping moving when contacting the bearing. Such instability is characterized by the shaft precession in the direction of shaft rotation at the eigenfrequency previously mentioned. This frequency is lower than the shaft rotation frequency.

It can be observed that the supply pressure increase from 0.2 MPa to 0.7 MPa moves the instability area from 370 to 630 Hz.

Displacement e (μm)



Rotational Speed (rpm)

Figure 8. *Dynamic shaft motion versus rotational speed for several supply pressure values*

Instability Related to Coupling to a Governing System

The seventeenth and eighteenth centuries were punctuated by the main stages of development of the steam engine and then spark ignition engines.

After the works and experimentations of Huygens, Papin, Newcomen and other scientists of this century, Watt thought to use the effects of the elastic force of steam, and no longer the weight of air, as motive force [HAR 95]. He then developed a governor capable of automatically adjusting the amount of steam inserted in the engine, and thus maintain a rotational speed roughly constant whatever the power supplied. For that purpose, he used a flyball governor.

The principle enables conversion of a rotational speed variation into a translational motion. Rods connected the heavy balls to a vertical shaft driven by the steam engine to be controlled.

When the engine ran too fast, the flyballs moved away from each other under the effect of the centrifugal force, the sliding collar on the shaft was raised and acted on the lever which slowed down the engine by reducing the steam inlet.

When the speed was too low, the lever acted in the reverse direction. This system is known to have been the first *feedback* mechanism used in industry.

The system as such had the drawback of being not very sensitive. Foucault had the idea to add a counterweight or spring system so as to amplify the motion of the flyballs due to a speed variation. As a matter of fact, these governors were too sensitive, which increased the risk of vibrations and instability.

Lenoir also used such mechanism to adjust the flow rate of the fuel mixture supplying his engine. Problems of oscillations were encountered on the first current generators where the Watt's governor was used to govern the speed.

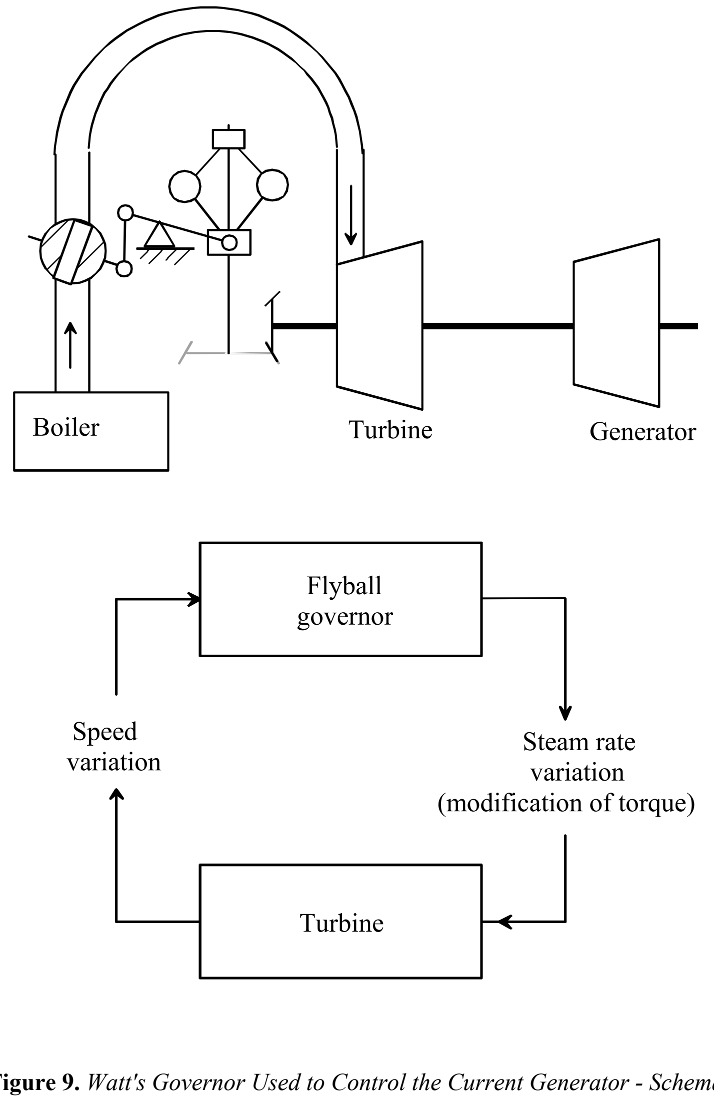


Figure 9. *Watt's Governor Used to Control the Current Generator - Schematic*

Such phenomenon, termed *hunting* [HAR 95], led to fluctuation of the light produced, visible to the naked eye.

The Authors are keen to thank:

– the Eurocopter company, for having authorized them to use the knowledge, experience and know-how developed by their employees for writing this work;

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