Mechanical Vibrations

Active and Passive Control

Tomasz Krysinski and François Malburet

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For all rotational machines, the analysis of dynamic stresses and the resulting vibrations is an important subject. When it comes to helicopters and piston engines, this analysis becomes crucial. From the design of parts working under stress to the reduction of the vibration levels, the success of a project lies mainly in the hands of the dynamicists.

The authors have combined their talents and experience to provide a complete presentation on the issues involved. Part one describes, in concrete terms, the main dynamic phenomena and how they can be observed in reality. Part two presents information about the modeling methods required to understand the dynamic phenomena and develop solutions capable of eliminating the most serious effects.

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Foreword

For all rotating machines, the analysis of dynamic stress and of resultant vibrations represents, at all times, an important subject. This analysis becomes crucial in the case of helicopters and piston engines. Be it the design of parts working in fatigue or the lowering of the vibratory level, the success of a project lies mainly in the hands of dynamicists. Throughout the history of helicopters there are many examples of devices whose commercial career was shortened, even interrupted, because their designer did not know how to obtain either a sufficient vibratory comfort or components working in fatigue whose service lives could be compatible to a competitive usage.

We must acknowledge the fact that, until recently, this field was governed by the wrong type of empiricism; certain constructors have dealt with prototypes of piston engines, rotors or different transmissions, all of them bound to lead to frequent as well as inexplicable failures.

Two specialists in dynamics, Tomasz Krysinski, head of the design department of Eurocopter, and François Malburet, teacher at l'Ecole nationale superieure d'arts et metiers, combined their talents and used their experience to present a complete collection on this aspect. It would be a good idea to praise in this collaboration an example of cooperation between an engineer in the field and a teacher-researcher at a reputed school, collaboration that is often recommended by the decision-making leaders but very rarely encountered in practice.

This book, the first of its kind on this topic, without insisting on complicated mathematical modeling, will describe in concrete terms the essential dynamic phenomena and the way they can be observed in reality.

The writer of these lines can guarantee the authors' skill in solving the issues related to the vibration control of helicopters, having been tested several times during test flights. The permanent confrontation between measurements during flights and theoretical analysis has very often led to brilliant successes, such as the vibratory level of the Tigre helicopter, and to the avoidance of instabilities which would have been likely to compromise the safety of the flight.

After reading this book, the student in engineering wishing to specialize in this field or the engineer working in the design department or in test flights will be able to acquire the knowledge and modeling methods necessary to understand dynamic phenomena and to develop solutions able to eliminate negative effects.

P. ROUGIER
Tigre Departmental Head
of Eurocopter Test Flights

Preface

In standard ISO 2041 the International Standards Organization defines vibrations as follows [BIG 95]: *"The variation with time of the magnitude of a quantity which is descriptive of the motion or position of a mechanical system, when the magnitude is alternately greater and smaller than some average value or reference."*

Dynamics is the science that deals with variations of physical units associated with vibrations according to time. This discipline is equally important for science and technology. Galileo studied the movements of stars. Newton, Lagrange, Euler and D'Alembert outlined the first theoretical ideas. Poincaré, Stodola and Timoshenko were a part of the industrial boom.

A few examples of historical practical work carried out in the field of vibration control are available.

Balancing machine

The first balancing machine was built by Martinson in Canada, in 1870 [LAC 79]. This machine did not find any practical application; however, the need to reduce the dynamic stresses in the bearings of swiveling elements was already present.

The first serial manufacture of balancing machines was initiated by Schenck in Germany at the beginning of the 20^{th} century. The balancing technique was perfected by improving measurement techniques and by choosing better correction places. In particular, the theory on balancing flexible shafts enabled the increase of the rotation speed of machines.

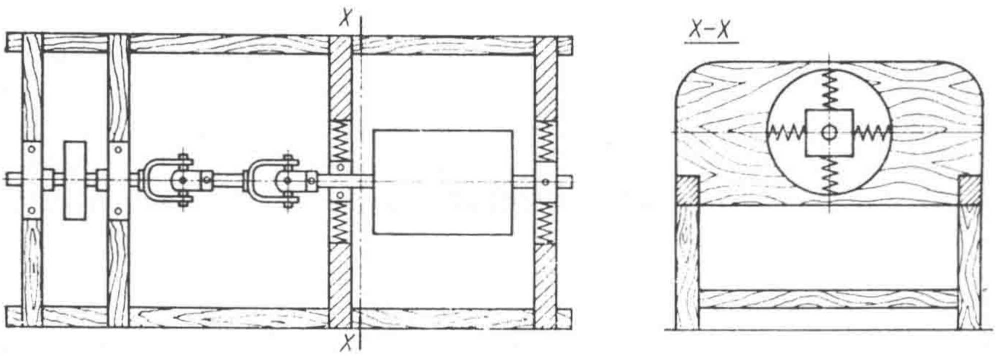

Figure 1. *The first balancing machine built by Martinson in 1870 [LAC 79]*

Dynamic absorber of torsional vibrations

The principle for a dynamic absorber comes from the need to process torsional vibrations on the crankshafts of a combustion engine. The first practical applications were carried out before World War II. In this respect, we can give the example of a torsional vibration absorber developed for an aeronautical engine by Havilland Engine Company between 1936 and 1938 [KER 68].

This absorber was used for the overcharged version of the Havilland "Gipsy" engine for versions 4 and 6 cylinders connected without an absorber and for version 6 cylinders connected with an absorber. This six cylinder engine with an absorber was the first mass production engine.

Nowadays, different versions of torsional dynamic absorbers are used for many combustion engines, such as some Formula 1 engines.

Suspensions and anti-vibration systems

Another significant example is the suspension of the transmission unit of a helicopter. This suspension was implemented for the first time on a Puma helicopter in France in the 1960s.

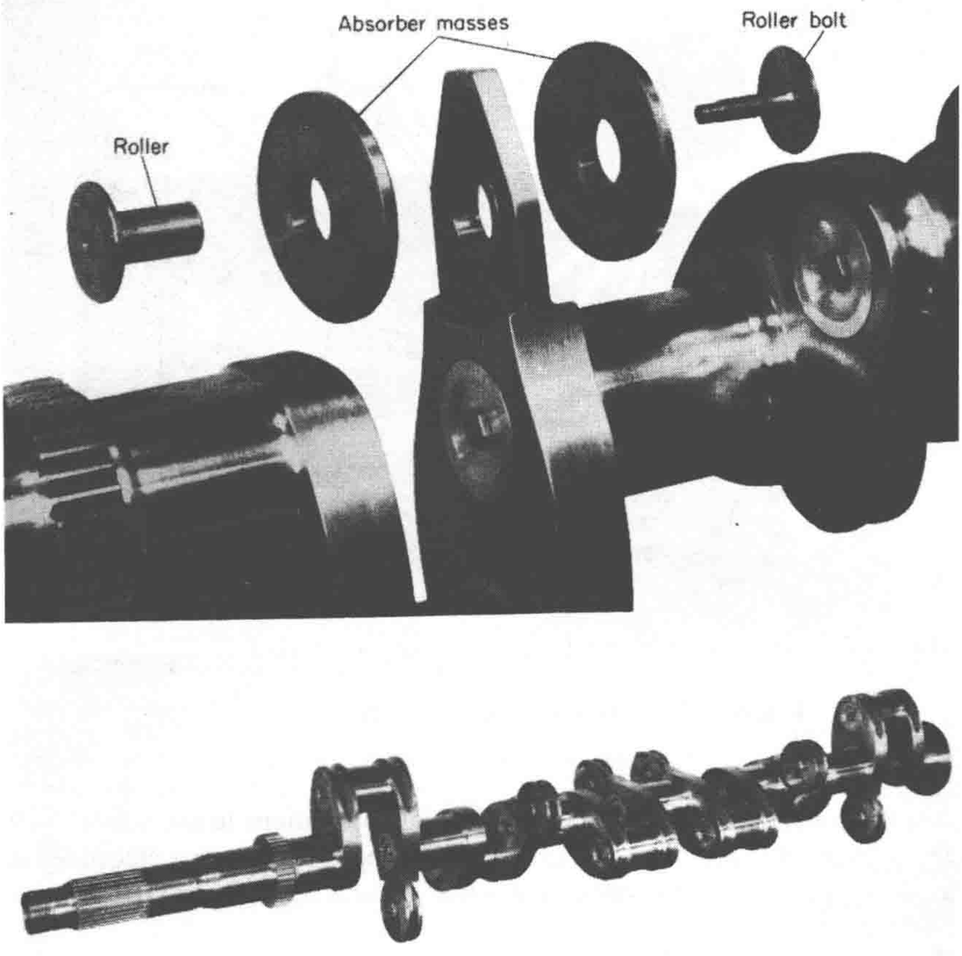

Figure 2. *Torsional dynamic absorber on an Havilland Engine Company engine [KER 68]*

The principle of insertion of a flexible element between two masses (the fuselage and the rotor) enables a significant improvement in cabin comfort.

These suspensions were largely enhanced by a better understanding of dynamic filtering techniques, by the introduction of elastomer elements, by the usage of resonators and by the arrival of semi-active and active systems.

The increasing need for comfort and the development of standards, particularly those pertaining to safety, urged industrialists to seek competitive solutions. The development of electronics and of digital systems constituted important elements in this rapid growth.

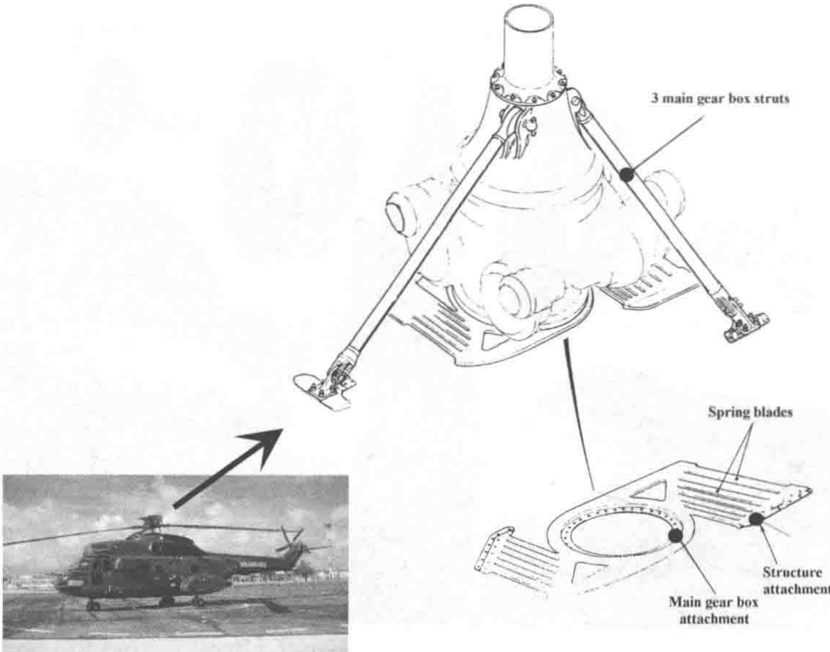

Figure 3. *First unit suspension on a Puma helicopter, 1965*

The helicopter was one of the first industrial applications to use active vibration control systems. For this, dynamic stresses are induced by actuators embedded in the structure. Figure 4 shows the embedded active systems on an EC725 helicopter.

The active and semi-active systems make it possible to correct certain mechanical systems defects and they produce better results than passive systems.

These few examples prove that dynamics is an innovative science that evolves continuously. The development of system requirements requires research for new solutions of phenomena modeling.

In the following chapters, the authors will provide examples of industrial problems of dynamics associated with their modeling and technical solutions.

The goal of this book is to outline certain elements which will enable an engineer to understand the problem of vibrations: it starts with the origin of excitations, continues with their minimization and concludes with passive and active filtering techniques.

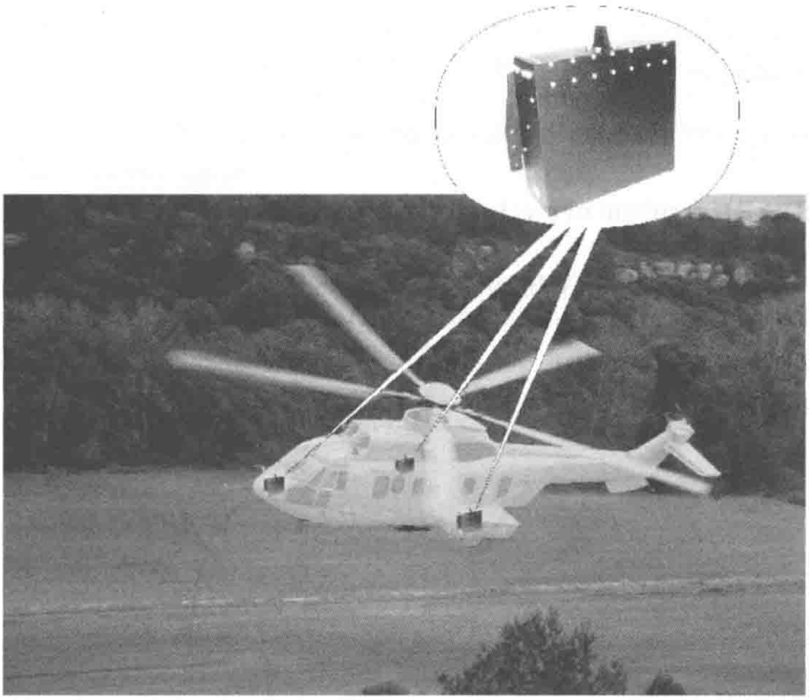

Figure 4. *EC725 helicopter with an active anti-vibration system. Photo C. Guarnieri (Eurocopter)*

D'Alembert's law proves the equality between inertial effects and stresses. Hence, for a solid non-deformable S, the fundamental principle of dynamics can be written in a torsorial form [AGA 86]:

$$\mathcal{D}\left(S/R_g\right) = \sum\left\{\overline{S} \rightarrow S\right\} \quad [1]$$

with:

– $\mathcal{D}\left(S/R_g\right)$: dynamic torsor of solid S with respect to the R_g inertial frame,

– $\left\{\overline{S} \rightarrow S\right\}$: torsor of mechanical actions applied to the solid.

This can be also formulated in two vector equations:

$$\begin{cases} m(S)\,\vec{A}_{G\in S/R_g} = \vec{R}\left(\overline{S} \rightarrow S\right) \\ \vec{\delta}_M\left(S/R_g\right) = \vec{M}_M\left(\overline{S} \rightarrow S\right) \end{cases} \quad [2]$$

with:

– m(S): mass of the solid,

– $\vec{A}_{G \in S/R_g}$: Galilean acceleration of center of inertia of S,

– $\vec{R}\left(\overline{S} \rightarrow S\right)$: resultant of mechanical actions outside of S,

– $\vec{\delta}_M\left(S/R_g\right)$: dynamic Galilean moment of S expressed in M,

– $\vec{M}_M\left(\overline{S} \rightarrow S\right)$: moment resulting from mechanical actions outside of S expressed in M.

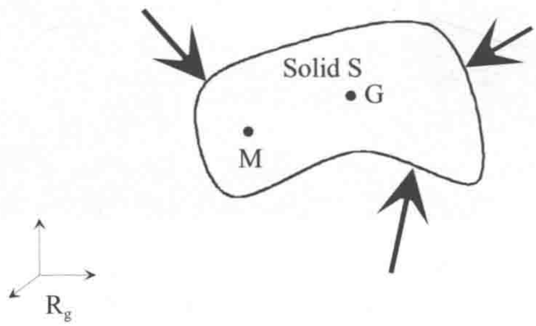

Figure 5. *The solid and its mechanical actions during its movement with respect to an inertial frame*

In dynamics, in order to generate vibrations represented by accelerations, there must be exterior mechanical actions, often called "excitations". These excitations can be of different types: unbalance, connection stress, aerodynamic stress, electromagnetic stress, etc,

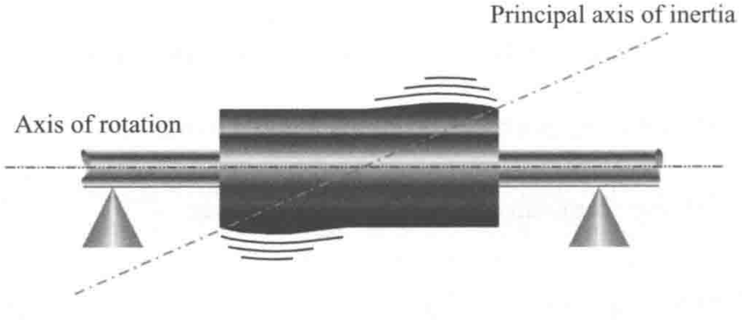

Figure 6. *Image of a non-balanced rotor, source of dynamic excitations. Photo C. Guarnieri (Eurocopter)*

Optimization of excitations is the main objective of engineers. However, it has its limits. The remaining dynamic stresses are often transmitted into the environment and this leads, in spite of everything, to pollution and damage. As a result, it is important to work on the transfer which constitutes a means of minimizing the negative effects of vibrations.

In order to avoid important dynamic constraints, natural frequencies of the structure must be positioned far from excitation harmonics. The Campbell diagram in Figure 7 shows the position of natural frequencies of helicopter rotor blades according to the speed of rotation of the rotor.

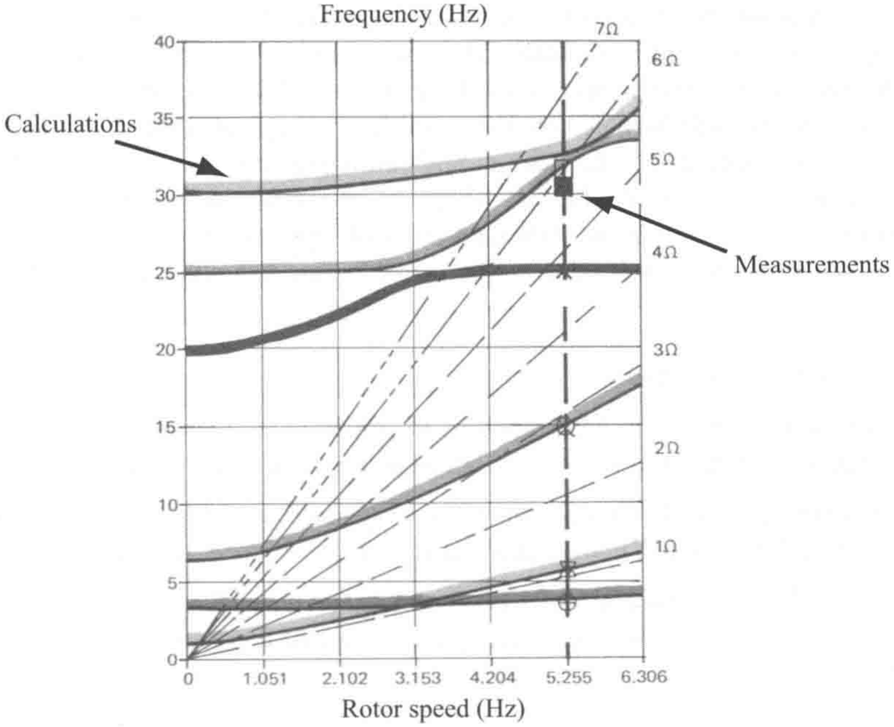

Figure 7. *Campbell diagram for a helicopter blade.*
Photo: C. Guarnieri (Eurocopter)

The notion of transfer combines together the insulations, suspensions, anti-vibration systems and the dynamic matching of mechanical systems. In particular we intend to deal with active systems that allow optimizing the transfer.

Mechanical systems get deformed and this entails, in certain cases, the problem of dynamic amplification. This dynamic amplification is associated with the notion of natural frequency or critical flow. The vibrations of deforming systems can be sufficiently important to cause destruction. When mechanical systems are exposed to increasing oscillations, they are referred to as unstable. Hence, it is important to study the stability of mechanical systems. The utilization field of modern mechanical systems is one in which the necessary stability margins are not enough and therefore active controls are needed.

Among industrial examples, the helicopter represents one of the most complex systems in terms of sources of vibrations. This fact is the consequence of its architecture and operating mode. This system comprises many swiveling systems with very different speeds of rotation, hence the problems related to unbalance, connections, rotors, aerodynamic excitations, etc. On this type of structure, the excitations stresses are relatively important in relation to the mass of the structure (fuselage). Aeronautical structures are light and therefore flexible. Natural frequencies can be close to excitation frequencies, which may entail problems of vibration comfort and alternate constraints in the mechanical parts. The problems of dynamic optimization of the rotor and structure are very important. This optimization may require the introduction of insulating elements, such as suspensions, anti-vibrators or vibration control systems for the blades. These systems can be passive, self-adaptive or active. Some examples will be developed here.

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