TWENTY FIFTH EUROPEAN ROTORCRAFT FORUM

Paper n° G – 7

G.A.H.E.L.
A NEW GENERAL CODE FOR HELICOPTER DYNAMICS
- CURRENT DEVELOPMENT STATUS -

BY

B. VIGNAL AND R. FERRER
EUROCOPTER, FRANCE

SEPTEMBER 14 – 16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA.

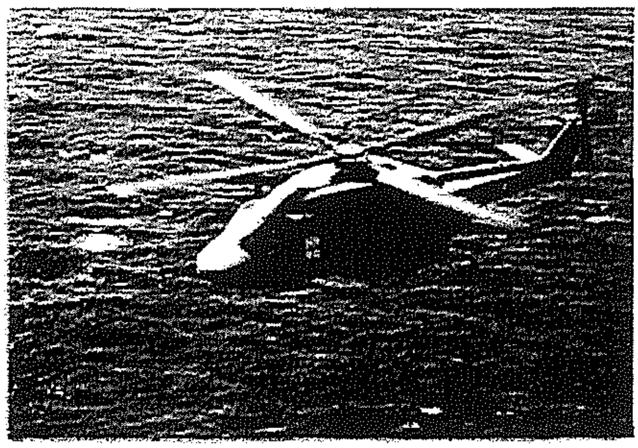
G.A.H.E.L.
A NEW GENERAL CODE FOR HELICOPTER DYNAMICS
- CURRENT DEVELOPMENT STATUS -

By

Berengere Vignal and Roger Ferrer

EUROCOPTER Dynamics engineers

Every new development program presents some difficulties in terms of dynamics. In fact, the general architecture of a new helicopter is decided during the project phase when the dynamic behaviour is not yet well known. This may have a high impact on the efficiency of the anti-vibration devices. Moreover, resolving dynamics problems during the development phase may impose fundamental modifications of the helicopter's geometrical design as well as costly delays.
The need for a general engineering code for helicopter dynamics that would provide simple answers is real.
G.A.H.E.L. (General Architecture of Helicopter) is meant to be an easy to use tool including a comprehensive database and simple models. It shall be used at the pre-project level to detect potential problems and give tentative solutions.
G.A.H.E.L. set-up begins with the creation of an updated database including the technical characteristics of every EUROCOPTER helicopter.
The parameters involved in the fundamental architectural selections as well as the optimisation of anti-vibration systems are then determined and a set of computing programs based on analytic models is developed.
These developments are validated with rig and flight-tests.
G.A.H.E.L. shall play a role in the virtual design and helicopters will thus be flown *"right from the drawing board"*.
This paper presents a new generation tool that will help engineers in achieving dynamics during every development phase.



1. Introduction

Reducing vibrations is a fundamental step in the development of a new helicopter. But the general architecture of this helicopter is imposed during preliminary design in most new programs. The modifications needed if problems occur can be difficult to complete and generate costly delays in the development process.
This is why EUROCOPTER decided to develop a new engineering tool known as G.A.H.E.L. including basic analytic models that can provide general architecture parameters, help to avoid fundamental problems and are able to optimise the vibration reducing devices. This tool will play a role in a new generation of codes.

Different points are discussed in this paper:
- G.A.H.E.L. contents
- Validation method
- Development strategy

2. G.A.H.E.L. contents

G.A.H.E.L. (General Architecture of Helicopter) belongs to a new generation of computing tools which are simple and open, have already been updated and capable of describing a virtual optimised helicopter.
Developed in EUROCOPTER Dynamics Department, G.A.H.E.L. is organised along two lines: a technical database and a set of computing programs. Thanks to this approach, G.A.H.E.L. covers every need in terms of dynamics.

GAHEL general organisation is presented in Fig. 1

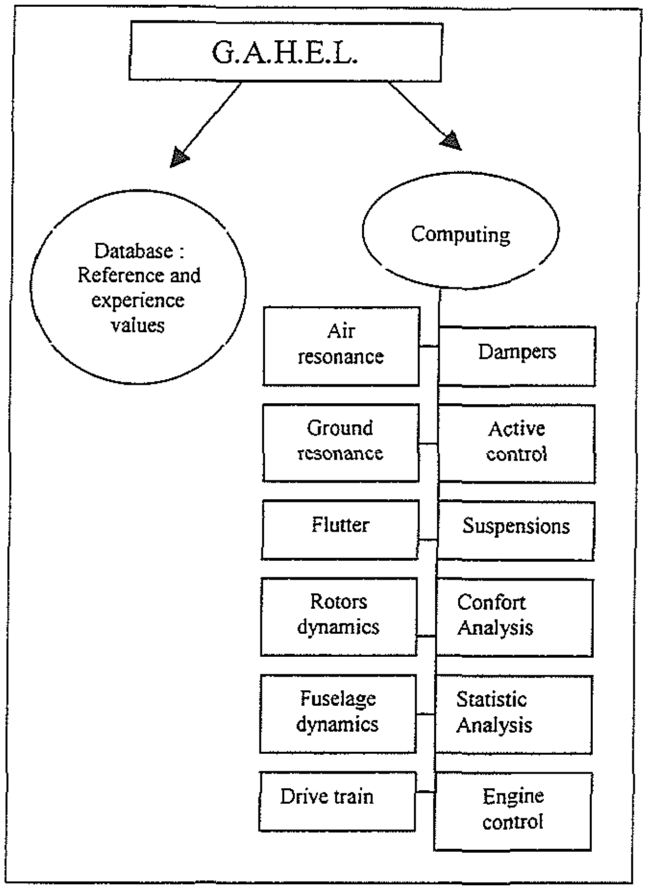


Figure 1 : G.A.H.E.L general organisation

2.1. Database:

The database includes technical characteristics for different helicopter sections:

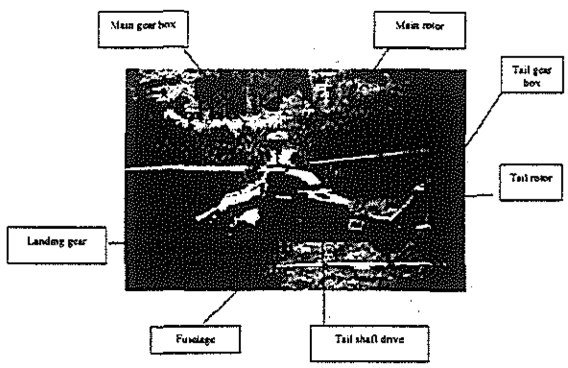


Figure 2: Helicopter sections included in G.A.H.E.L.

- The main rotor: type (hinged, Spheriflex, Starflex), nominal speed, idling speed, autorotation, number of blades, radius, blade mass, inertia, static moment and eccentricity, centrifugal load at the nominal speed, aerodynamics data, modal data (lead-lag and flapping modes), rig tests data.

- Ditto for the tail rotor.
- The fuselage : total mass, inertia in each direction, position of the centre of gravity and rotor hub, modal data.
- The landing gear: type (wheel or skid), geometric and material description.
- The main gearbox: power, geometrical characteristics.
- Ditto for the tail gearbox:
- and the intermediate gearbox:
- The tail rotor drive: shafts description : material (Young modulus and density), cross-section, length, number, tube description, bearings (distance and number), modal data (frequencies computed and measured).
- The suspensions: geometrical description, mechanical characteristics.
- The drive train : geometry, inertia, stiffness and damping.

The database includes reference as well as test results for EUROCOPTER production rotorcrafts.

2.2. Set of programs:

During the pre-project phase G.A.H.E.L. shall be used to detect potential dynamics problems and optimise the geometric parameters involved to improve dynamic characteristics.
The programs are based on analytic models computing the frequencies and vibration modes of a system, authorising stability studies and providing information for the selection of a basic architecture.

This set of programs can be divided into several sections:
- Stability programs.
- Natural frequencies and modes determination.
- Anti-vibration devices optimisation.
- Statistic analysis.

The different models are:

2.2.1. Stability programs:

Ground resonance stability:

In ground resonance mode, the body modes are generated by the structure proximal to the landing gear. Ground resonance occurs whenever the frequency of the fuselage on the ground is close to the lead-lag frequency in the fixed system (figure 3).

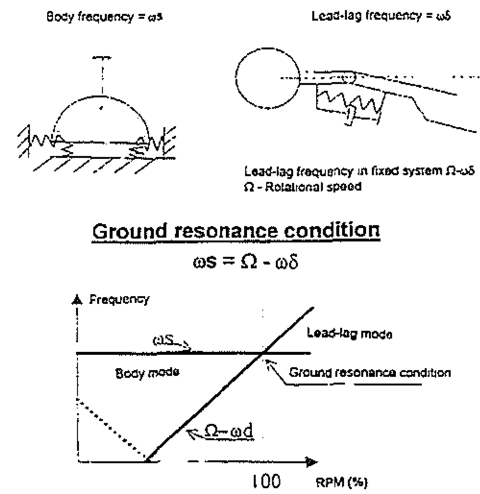


Figure 3 : Ground resonance phenomenon

Obtaining satisfactory stability margins is one of the prime concerns in the current helicopter design.

The main difficulty with this design is the non linearity of the lead-lag damper and the landing gear characteristics.

A stable helicopter can thus become unstable when the pilot excites ground resonance by precessing the cyclic pitch in the rotor's sense of rotation, due to the modification of dynamic characteristics with non linearity phenomena.

The basic ground resonance theory was originally developed by Coleman.
The first lead-lag mode and the hub in plane are the degrees of freedom taken into account in the analysis.
The helicopter fuselage is represented by a rigid body with pitch and roll rotations.

The system's equations are expressed by the Lagrange method. The linearized periodic coefficient perturbation equations are converted into a constant coefficient system with Coleman's transformation proceeding as follows (four bladed rotor):

$$\beta_i = \beta_0 + \beta_{1C}.\cos(\Omega t + (i-1).\frac{\pi}{2}) + \beta_{1S}.\sin(\Omega t + (i-1).\frac{\pi}{2})$$

$$\delta_i = \delta_0 + \delta_{1C}.\cos(\Omega t + (i-1).\frac{\pi}{2}) + \delta_{1S}.\sin(\Omega t + (i-1).\frac{\pi}{2})$$

$$\theta_i = \theta_0 + \theta_{1C}.\cos(\Omega t + (i-1).\frac{\pi}{2}) + \theta_{1S}.\sin(\Omega t + (i-1).\frac{\pi}{2})$$

The system is also expressed with:

$$M.(X_0).\ddot{X} + C(X_0).\dot{X} + K(X_0).X = F(X_0).\theta$$

where X is the co-ordinates vector, X_0 is the equilibrium position vector and θ are the control inputs.

X^T=[x y z α_x α_y α_z β_0 β_{1C} β_{1S} δ_0 δ_{1C} δ_{1S} θ_{MR} θ_{MGB} θ_{ENG1} θ_{ENG2} θ_{TR}]

θ^T=[θ_0 θ_{1C} θ_{1S}].

The equations are then transformed into a first order form:

$\dot{x}$=A.x+B.u
y=C.x
where x is the state space variable vector, y is the output measurements vector and u is the input excitations vector.

The rotor operating limits where the system is secure can easily be determined when studying two graphics describing the evolution in damping and the frequency of the modes involved.

Air resonance stability:

Air resonance is a coupling phenomenon between the rolling movement of the fuselage and the lag movement of the blade. It can be defined as an extension of ground resonance.
Several rotorcraft degrees of freedom are involved. Some displacement on roll axis induces a pitch increment on the back blade followed by a flap reaction generating a lag reaction.
Air resonance occurs when the rotor load factor is high or upon a turn at altitude, ...
This phenomenon generates instabilities and can jeopardise rotorcraft safety.
The model developed takes the degrees of freedom involved into account and studies stability with a Bode diagram.
Several gear train analytic models are being built to study air resonance.

Flutter:

Flutter phenomenon can be defined by a coupling of bending and twisting movements of the blades.
The first bending and twisting mode frequencies are computed and a graphic stability study is undertaken.

Drive train stability :

The helicopter drive train system is composed of rotors, engines, shafts and gears.

This system can generate different dynamic problems such as torque oscillations and rotor speed variations degrading handling qualities.

The dynamic analysis of the helicopter drive train is mainly focused on two points:

- suitable tuning of the system's torsional modes, providing a proper separation from bΩ as well as 2bΩ excitation frequencies. The lead-lag stiffness of the blades is often adjusted to raise this mode over bΩ and obtain a sufficient safety margin with respect to this excitation.

- adaptation of fuel controlling engine governor to the dynamic characteristics of the system in order not to decrease the natural damping of the first torsional modes.

High engine governor gains will ensure satisfactory accelerations but may lead to unstable coupling of the first drive train mode according to engine behaviour.

Finding a compromise between accelerations and drive train stability is a major problem, mainly as regards inter-blade technology because there is no damping of the lead-lag dampers on the 1st drive train mode.

The mathematical model representing the vibration behaviour of the helicopter in the [0 10 Hz] frequency range was designed from models describing ground or air resonance.
The fuselage is represented by a rigid body with yaw, pitch and roll rotation as well as vertical, lateral and longitudinal translation.
The landing gear is assimilated to perfect dampers and springs.
The blades are assumed to be rigid. The degrees of freedom taken into account are the pitch, lead-lag and flapping movements.
The torsional angles between the different components are defined .
The system's equations are determined with the Lagrange method.
The models help analyse the torsional dynamics of the drive train system as a whole.
The non-linear engine characteristics are linearized about a steady condition.
The stability margins are derived from a Bode diagram.

2.2.2. Natural frequencies computation :

Natural frequencies computation provides inputs for stability studies.

Determination of the fuselage natural modes:

Whenever a ground resonance study is undertaken, the fuselage modes are computed while assuming the rotorcraft is on the ground. Equivalent landing gear stiffness and damping are required to determine the modal deflections and frequencies of the fuselage.
This modulus computes modes for the wheel and skid landing gear.
The wheel landing gear is assimilated to perfect springs and dampers in the three axes for each wheel (figure 4).

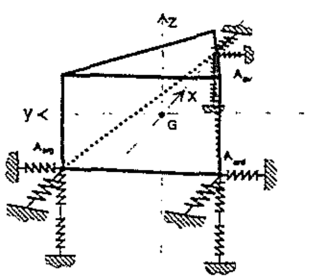


Figure 4 : Landing gear modelling

The optimisation procedure allows placing the frequencies in a specific area.

Determination of the natural blade modes:

The code computes the natural blade modes. The sensitive study is integrated and the optimisation procedure is made available.

Determination of the tail rotor drive natural frequencies:

The tail shaft can be classified in two categories:
- Sub-critical: Every natural frequency is superimposed to the speed of the tail rotor drive shaft.
- Super-critical: one of the frequencies is computed under the drive velocity.

The model computes the first five natural frequencies and modes and the margins are displayed with a graphic study taking the rotor bΩ frequencies and the tail drive speed into account.

2.2.3. Anti-vibration devices:

The anti vibration devices are broken down into 3 classes:

- rotor hub
- rotor-to-fuselage interface - upper deck
- fuselage.

Three categories (passive, semi-active and active systems) are distinguished in these three classes These technologies are described in figure 5.

	PASSIVE	SEMI ACTIVE	ACTIVE
ROTOR HUB	RESONATORS : -PENDULUM MASS -BIFILAR -HUB ABSORBER -ROLLER ABSORBER	Auto-tuned Hub absorber	HHC IBC
UPPER DECK	BBQ SARIB ARIS RESONATORS	Auto-tuned SARIB	ACSR
CABIN	MECHANICAL RESONATORS	Auto-tuned resonators	Cabin actuators

Figure 5 : Summary of anti vibration devices.

Dynamic absorbers :

Blade or hub-mounted dynamic absorbers (pendulum mass, bifilar, hub or roller absorber) are the most popular anti vibration devices used in helicopters. The resonance tuning of these dynamic absorbers must be close to the rotor harmonic to be reduced.
The code allows computing the characteristics of dynamics absorbers in terms of geometry and tuning characteristics.

Upper deck suspensions :

Eurocopter was one of the first helicopter manufacturers to offer a focal point suspension system, so-called "barbecue", on the market. This system was applied to the SA 330 Puma. The idea was to use soft elements to filter vibrations in the gearbox sump. The satisfactory results obtained in SA 330 boosted the development of several derivatives in AS 332, Dauphin and Ecureuil. A simplification is produced with the use of laminated elastomer mounts and flexible composite bars.

A new generation of suspension system so-called "SARIB®" was developed in recent years.
SARIB® is an anti-resonance isolation system, consisting, as shown in figure 6, of 4 individual units equi-spaced around the gearbox. One of those units

includes a leaf spring, the flapper arm and flapper mass. The leaf spring is designed with two parallel flanges at the stiff end. One bolt connects, through the outer bearing, the leaf spring, to a bracket on the gearbox deck and another bolt connects the leaf spring to a gearbox strut. Elastomeric bearings are provided at both connections.

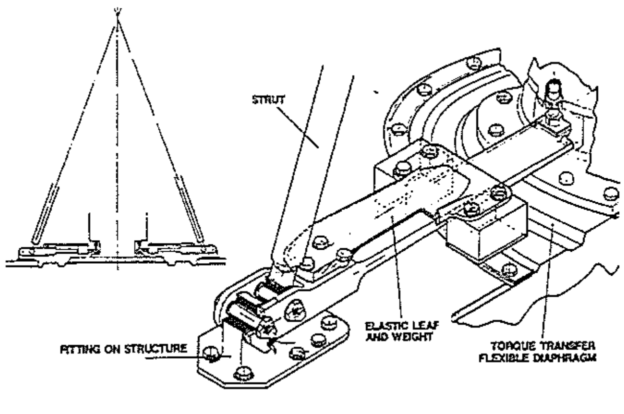


Figure 6 : SARIB Anti-Resonance isolation system

The elastic side of the leaf spring is supported at the bottom of the gearbox. The amplification needed for flapper mass oscillation is realised through the flapper arms and their connections to the stiff part of the leaf spring, close to the gearbox strut. A membrane provided between the bottom of the gearbox and the fuselage transmits the rotor torque. Excellent vibration levels were achieved with SARIB® isolation for different missions and weapon configurations.

The model allows optimising the basic architecture of this suspension and provides the necessary tuning.

These models help select the most suitable device for the application. Moreover the anti vibration system is optimised.

Active control :

The main idea behind the active control of air-mechanical stability is being able to use the hardware that is already available in the helicopter.

Air/ground resonance can also be achieved provided the proper compensation is introduced in a body state feedback loop.

The first step is to select parameters that are easily available in the helicopter (accelerations, angular velocities in the fixed system) as far as the observation variables of the phenomenon are concerned.

The helicopter is then identified for the observed phenomenon and the model can be generated. Control laws were developed with simulations at this stage.

Active control is based on the injection of a cyclic control into the rotor calculated from a parameter measured in the fixed datum.

Theoretical studies were also conducted for active stabilisation of the 1st drive train mode for inter-blade rotors, in particular.
The objective is the reduction of high resonance in the frequency areas where engine governor laws are still active and with sufficient gains to maintain satisfactory accelerations.

The theoretical model integrated in G.A.H.E.L. allows elaborating the control strategy and the control loop is made.

2.2.4. *Statistical Analysis:*

This part of G.A.H.E.L. computes similitude laws for several geometrical parameters of the helicopter.
The modulus designed with database figures and test results allows comparing rotorcraft; new helicopter architectures can then be defined from these laws.

These programs are set up for G.A.H.E.L. application, tested and validated on the rig and in flight as well as with a number of previous applications.

3. Validation method.

Each code developed and integrated in G.A.H.E.L. must be validated. The devices used to do this can be divided in two categories: the first involves using a previous computing tool provided to give satisfactory results. The second method involves using test results.
The same conditions are to be applied for both. Moreover, a non-regression of the codes must be demonstrated whenever modifications are made. Every option delivered must be tested.

The first case reported involves the vibration modes of a tail rotor drive.
This code was validated along two lines : a finite-elements model designed with SAMCEF software and a test performed in EUROCOPTER laboratories. The same tail rotor drive (Super Puma MK2) was used in every configuration.
The second case reported is the validation of the drive train simulation made on the Super Puma MKII.

3.1. Tail drive shaft:

3.1.1. G.A.H.E.L.:

This study is based on an analytic model made with finite elements. Beam elements are selected with displacement in two directions and bending rotation. The mass and stiffness matrices are manufactured, the eigen values and vectors are computed. The first three bending frequencies are determined. Figure7 presents the architecture of the Super puma MKII tail rotor drive as used in G.A.H.E.L..

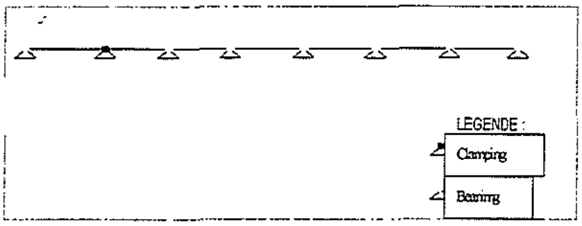


Figure 7 : Super Puma MKII tail drive architecture.

The first bending modes computed are:

1. 167.5 Hz : resonance of the first section
2. 171.5 Hz : resonance of the central section
3. 185 Hz.

The modal deflection of the second vibration mode is given on Figure 8.

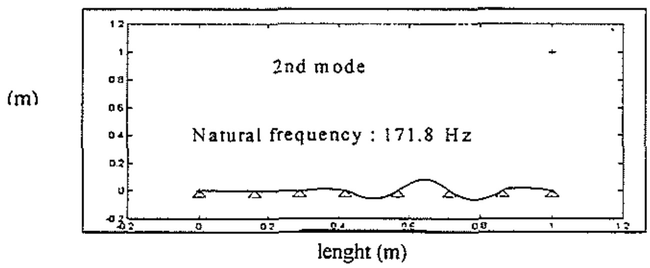


Figure 8 : 2^{nd} modal deflection : G.A.H.E..L computation.

3.1.2. Test on the aircraft :

The purpose of the test is to identify the natural vibration modes of the tail rotor drive.
The study was limited to the second frequency: 170Hz, resonance on the central section.

3.1.3. F.E. model:

The F.E. model is embodied with SAMCEF application. The elements used are beams with displacement and rotation in all directions.

The displacement in the X (length) and Y (bending) directions are fixed on the nodes connected to a bearing element.
The results for the first bending frequencies are:
165.5 Hz: resonance of the first section.
170 Hz: resonance of the central section.
183.7 Hz.

The modal deflection of the second mode is presented in figure 9.

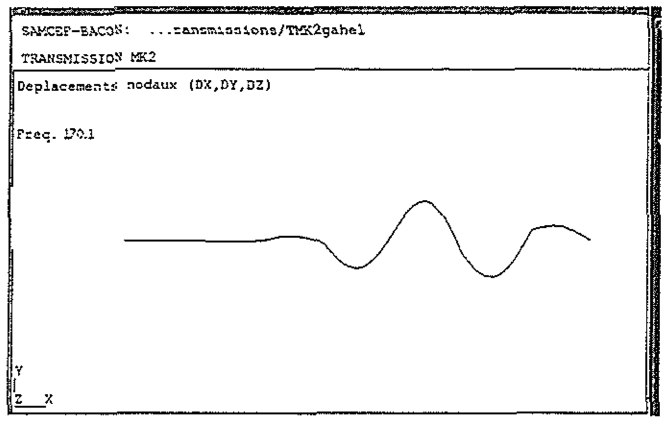


Figure 9 : 2^{nd} modal deflection : SAMCEF computation.

3.1.4. Summary:

The results are summarised in the following table:

	FE model	TEST *	G.A.H.E.L.
1st mode			167.5 Hz
2nd mode	170 Hz	170 Hz	171.5 Hz
3rd mode	183.7 Hz		185 Hz

*: Only the second mode was measured during this test.

The correlation between the three values is satisfactory. The G.A.H.E.L. tail rotor drive model provides acceptable results.

3.2. Drive train :

The validation proceeds on the first drive train mode of the Super Puma MKII.
The simulations undertaken with the analytic model and flight test results in the prototype are compared.

The transfer function study shows that two modes of resonance are produced either when the rotor is excited with the collective lever (θ_0) or when the fuselage is

excited in yaw. Excitations with the cyclic stick do not produce any drive train / rotor / fuselage coupling.
The first mode frequency is 2.7 Hz and the second is 6Hz.

The parameters measured on the drive train already instrumented, are the main rotor mast and the engine shaft torque.
A preliminary study undertaken by Eurocopter shows that the engine governing system tends to amplify resonance in the 2.7 Hz but is insensitive to vibrations around 6 Hz.
The tests were thus intended to detect the 2.7 Hz mode.
Excitations were generated by the automatic flight control system with the collective lever. The excitation was sinusoid.

Figure 10 presents a comparison between the temporal responses for parameters measured and determined with a G.AH.EL. simulation throughout the mast torque excitation period.
The amplitudes are the same and a resonance occurs at the same frequencies.

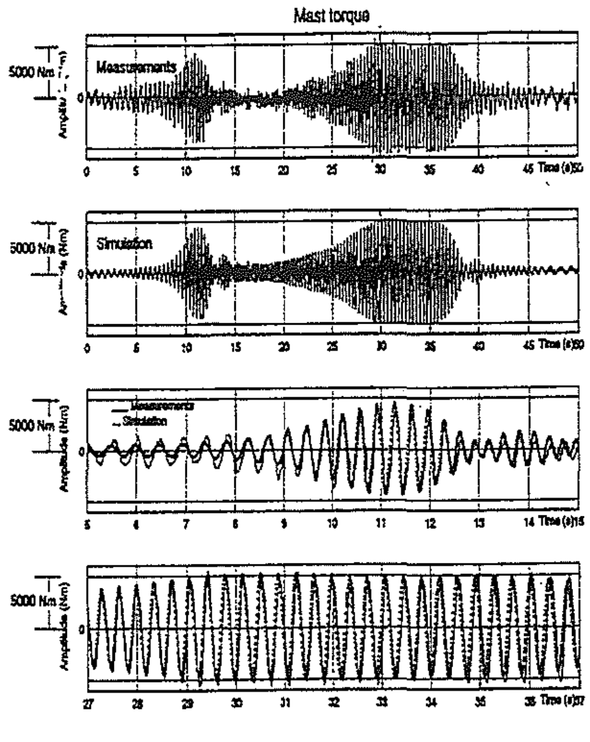


Figure 10 : Drive train identification : calculation/measurement comparison.

3.3. Conclusion:

The same method is applied for every computing program. The reference codes used for comparison purposes with G.A.H.E.L. can be programs that were validated in the past.
Many flight and rig test results are available in EUROCOPTER Dynamics Department for comparison with G.A.H.E.L. results.
Moreover, a model adjusting method is to be developed to limit the number of tests undertaken for G.A.H.E.L certification.

4. Development strategy

The objective is to create a simple standard tool which is easy to use, safe and cheap.

G.A.H.E.L. is developed in a unified environment.
MATLAB (version 5) application is used to generate the codes and Microsoft® EXCEL application to create the database. MATLAB is both an interactive environment and a language. It is technically highly efficient because of its high matrix computing capabilities. G.A.H.E.L. runs on a PC increasing facility of access and purchase.

The figures drawn from the EXCEL database are identified by their name rather than their values. The modifications made to the data base consequently have no impact on the validity of the programs.

Each program is validated and the non-regression code is provided for any modification.
The software is constructed program by program and this makes it easy to add a new model.

5. Conclusion

G.A.H.E.L. is a new general code for helicopter dynamics. It will include a set of computing programs and a technical database. Every development is validated with rig and flight tests.

Aeronautic tests are technically difficult to prepare and expensive to achieve.
The general trend is to develop a new generation of tools that will help certify a new aircraft or rotorcraft with a minimum of tests.
G.A.H.E.L. will play a significant role in this new approach.

G.A.H.E.L's future is the development of a link between codes to produce a software able covering every dynamic investigation.

6. REFERENCES:

1. **F. BEROUL - L. GIRARD - E. ZOPPITELLI, T. KRYSINSKI**
« Current state-of-the-art regarding helicopter vibration reduction and aeroelastic stability augmentation »
18th European rotorcraft Forum, 15-18 IX 1992 - Avignon

7. M. ALLONGUE – T. KRYSINSKI
" Validation of a new general aerospatiale aeroelastic rotor model through the wind tunnel and flight tests data".
46th Annual Forum of the American Helicopter Society, Washington DC, May 1990.

3. T. KRYSINSKI
"Active control of aeromechanical stability".
AGARG symposium, Ottawa Canada, May 1996.

1. R.P. COLEMAN and AM INGOLD
"Theory of self-exited mechanical Oscillations of rotors with hinged blades"
NACA report 1351, 1958.

2. P. ALMERAS
"Active control of aeromechanical stability applied by Eurocopter"
23th European Rotorcraft Forum, Dresden, Germany, September 1997.