"ADVANCED CONCEPT OF DRIVE SHAFT SYSTEM FOR HYBRID HIGH SPEED HELICOPTER"

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Key words: hybrid helicopter, demanding working conditions, supercritical shaft.

Abstract: In this paper, a new advanced concept of supercritical drive shaft system has been described. It is intended to work inside an aircraft's wing, in very demanding conditions, such as narrow available space with a simultaneous significant relative displacement between sub-systems, transmitting higher mechanical power than conventional shafts. The standard approach, to design drive shafts, has been reconsidered and adapted to new requirements. This technology has been applied first to the X3 demonstrator and is pushed to a new leading edge level on the Rapid and Cost- Effective Rotorcraft (RACER) demonstrator. It is a hybrid high speed helicopter funded jointly by Airbus Helicopters and European Commission in frame of Clean Sky 2.

1. Introduction

The design, substantiation and industrialization processes, for the transmission shafts, are well known and mastered in rotorcraft industry. Currently leading applications use supercritical, 1st mode at least, transmissions between main gearbox (MGB) and tail gearbox (TGB). An example of such application and profits related to, are shown below in Figure 1 and Figure 2.

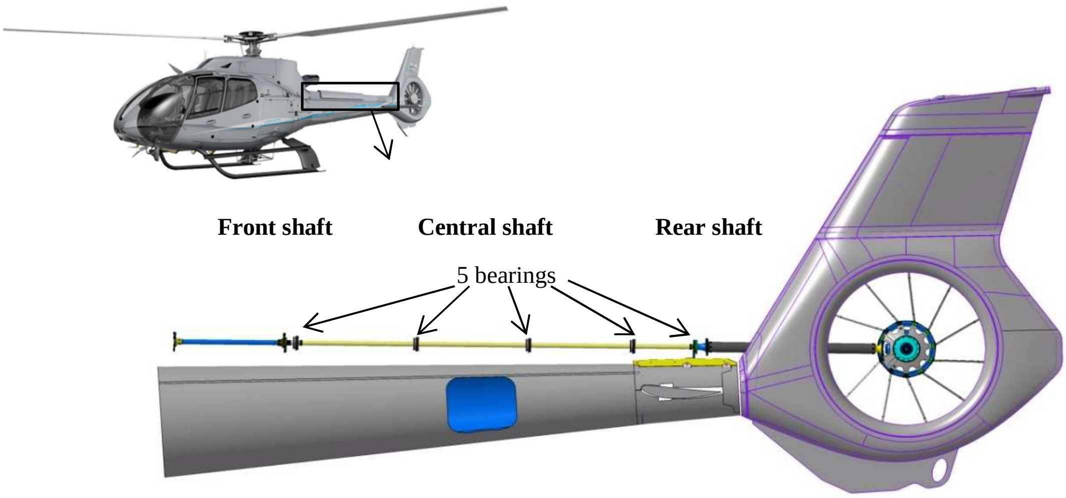

Figure 1: H130 subcritical tail driveline (TDL) - before upgrade

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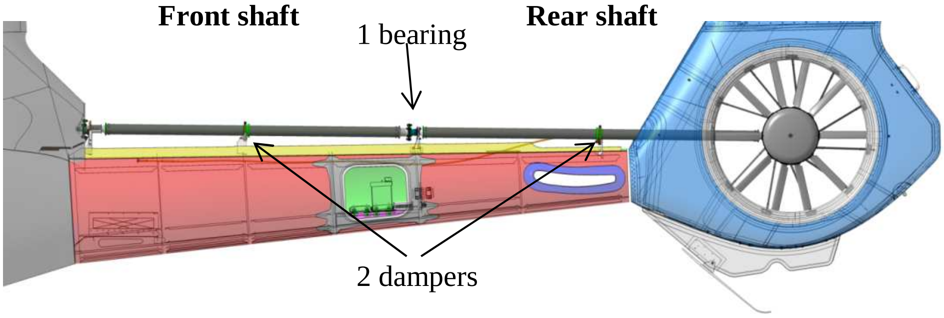

Figure 2: H130 supercritical tail driveline (TDL) - after upgrade

Analysing H130 TDL, advantages of supercritical drivelines, comparing to subcritical ones, are clearly visible:

- Lower weight;
- Less complex integration with environment;
- Reduced amount of grease lubricated bearings;
- Less complex maintenance;
- Reduced costs.

Supercritical drivelines development process is much more complex than subcritical ones. However benefits of using them are very encouraging.

One of the main targets for RACER demonstrator is to be 50% faster than conventional helicopters, with a cruise speed up to 220 knots (400 km/h). Something, which is out of reach for “legacy helicopter’s architecture” is at fingertips for the hybrid construction. It is characterized by wings with pushing lateral rotors, responsible of cruise speed increasing. The supercritical drive shafts, called in RACER Lateral Drivelines (LDLs) installed inside the wings, transmit mechanical energy from MGB to Lateral Gearboxes left hand side (LH LGB) and right hand side (RH LGB). It means the LDLs contribute in achieving high speed target. RACER visualization is presented in Figure 3.

Figure 3: RACER’s hybrid architecture

2. Advanced concept of the Lateral Driveline

Non- conventional RACER’s design determines more demanding requirements for the LDLs. From this reason, the standard approach of developing the supercritical drivelines has been reconsidered and adapted to the new conditions. It imposes several original solutions implemented in the LDLs.

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2.1. Architecture

The LDL is roughly 3.4 m long, it is connected directly with MGB and LGB by means of flexible elements called soft couplings, only a friction damper is attached to the wing. There is no bearing maintains the shaft. It is an effect of deep analysis. Potential bearing could be installed onto the wing's rib. However its multidimensional deformation during various manoeuvres would create an additional load on the shaft. Bearing's installation with respect to the LDL axis and related maintenance operations would be very problematic as well. Additionally, the bearing would increase weight of the system and impose bigger wing's section which creates negative effect on an aerodynamic performance. From the other side lack of bearings is more challenging for LDL perimeters. Taking into account all aspects, "without bearing" architecture was selected as more profitable at the aircraft level.

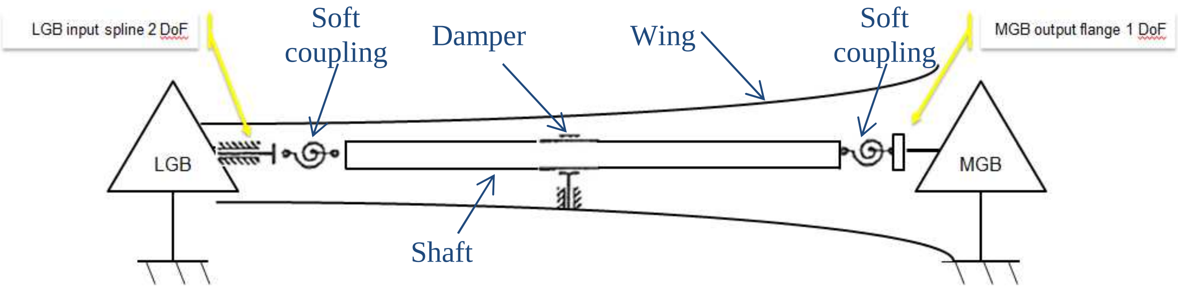

Figure 4: LDL architecture

2.2. Shaft

Shafts of the supercritical tail drivelines are assembled from several parts:

- Tube;
- Flanges;
- Friction ring;
- Rivets.

That is the best trade-off between performance, costs and weight.

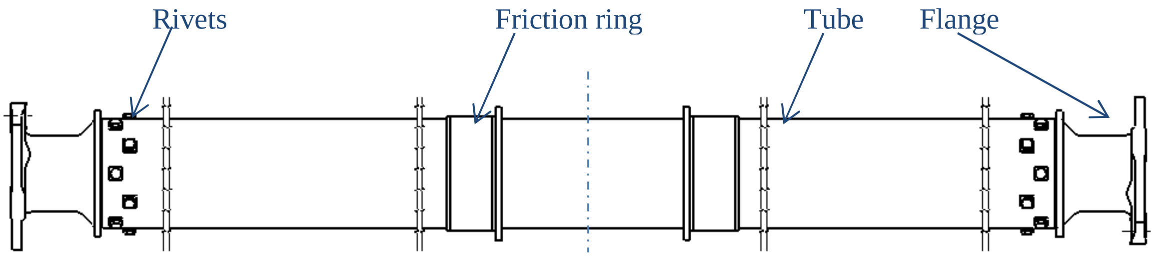

Figure 5: Conventional shaft's construction

Similar solution has been analysed for the LDL, however due to specific working conditions has been rejected. Table below relates main parameters which impose new shaft's approach.

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	Conventional drivelines	LDL
Torque [Nm]	(ref.)	(~3x)
LDL speed [rpm]	~4300 (ref.)	~ 3300 (~0.7x)
Main Rotor speed (MR) [rpm]	~330 (ref.)	~270 (~0.8x)
Tail/Lateral Rotor (TR/LR) speed [rpm]	~ 1000 (ref.)	~ 1700 (~1.7x)
LDL/structure displacement	Ref.	~5x
LDL/gearboxes displacement	Ref.	~2x

Table 1: Comparison of working conditions for conventional drivelines and the LDL

Analysing Table 1, several important conclusions have been listed:
- Such a high load requires significant increasing of thickness and/or material of a tube's modification;
- Rivets are not capable to transfer such the high load, new way of tube-flanges connection had to be developed;
- Differences in rotational speeds of rotors and the LDL effect unlike resonance frequency of the shaft;
- Due to high relative displacement between the LDL and the wing, and the wing's section constrain, the tube external diameter shall be minimized. This point has a major impact on dynamic and stress aspects.

To size properly this part, in a first step, critical frequencies of the LDL have been positioned in a global frequencies spectrum, in order to avoid any excitation in normal working conditions. For this purpose the analysis, based on Campbell's diagram [1] was used.

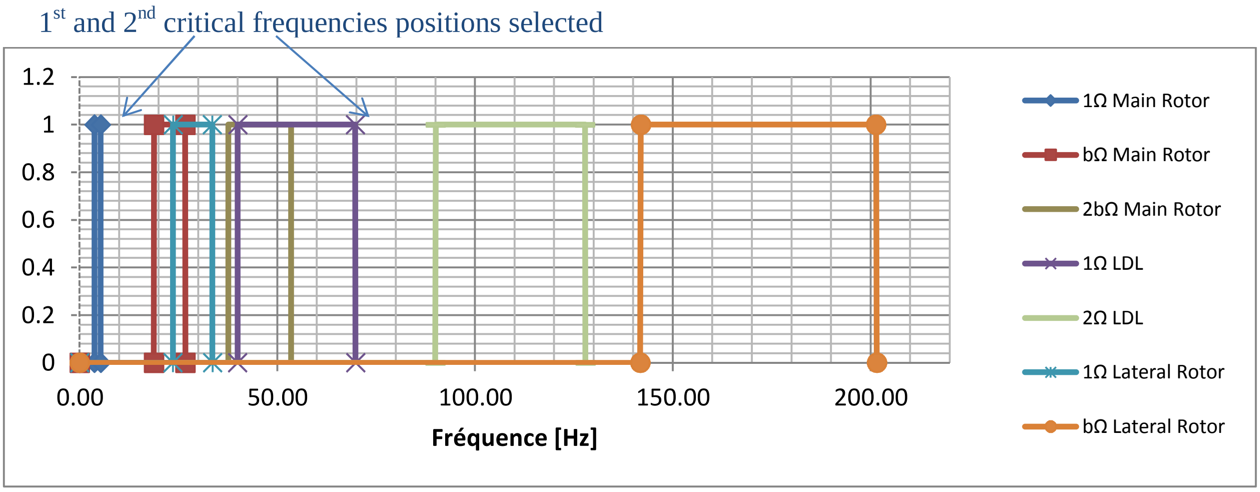

Figure 6: Campbell's diagram- windows version

All frequencies occurring in normal working conditions, including safety margins have been considered and visualized in Figure 6. Realistic windows for the LDL critical frequencies are only two, pointed in Figure 6, so the 1st critical frequency is placed around 17 Hz. It is roughly 50% lower than in the conventional drivelines.

Equation (1) is an analytical formula, enables to obtain fast, preliminary results of natural frequencies of shafts, by modifying geometrical and material features of them. To use it, the LDL was considered as a long, thin cylinder linked with articulations on both extremities. The articulations are a simplification of the soft couplings, because at this level there were no data about the LDL's flexible parts. Taking into consideration conclusion of Table 1, the frequencies calculations have been prepared for aluminium, and stainless steel.

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(1) $$f_i = \frac{1}{2\pi} \cdot \frac{a_i}{L^2} \cdot \sqrt{\frac{E \cdot I}{\rho \cdot S}}$$

Results of simplified calculations have not brought a realistic solution. When the 1st critical frequency matches in the selected area, the 2nd critical frequency crosses the forbidden one. In contrary when the 2nd critical frequency matches in the selected area, the 1st critical frequency crosses the forbidden one, as it is visualized in figures below.

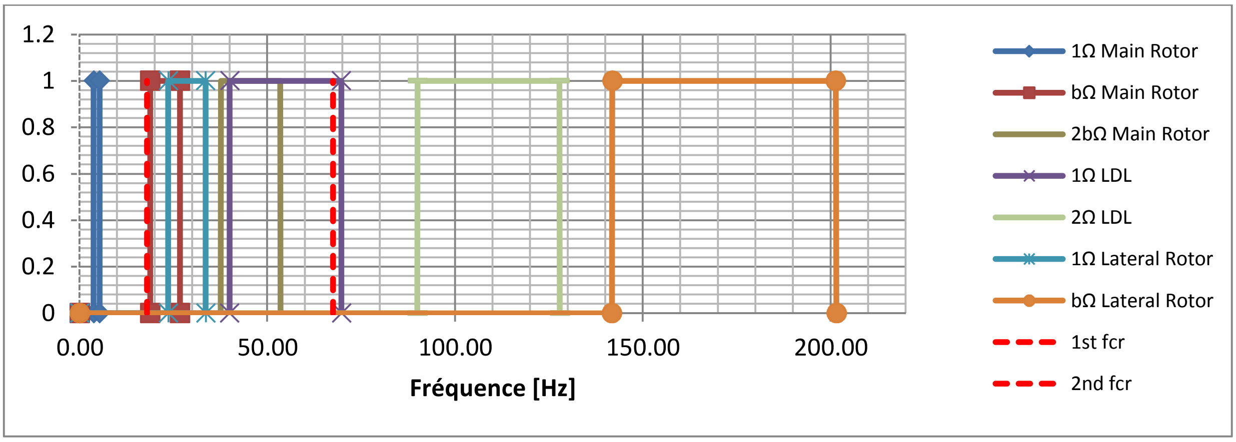

Figure 7: 2nd critical frequency in the forbidden area

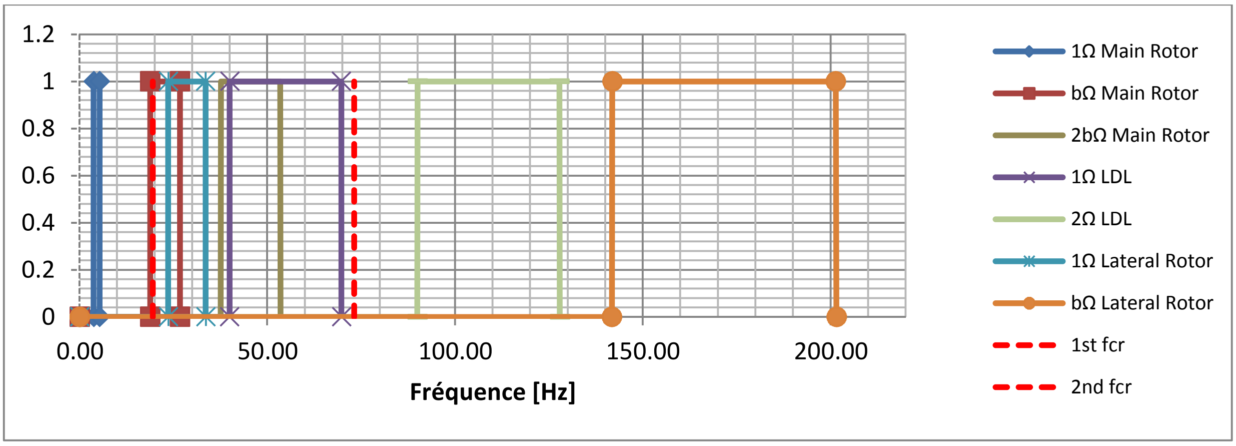

Figure 8: 1st critical frequency in the forbidden area

The main difficulty comes from a constant relation between the 1st and the 2nd critical frequencies described by (2).

(2) $$f_2 = \frac{a_2}{a_1} \cdot f_1$$

Where $a_1$and a_2 are coefficients defining a link type on the shaft extremities, unique for each critical frequency. Visualizing them (Figure 7 and Figure 8), a distance between both critical frequencies is unchanged regardless dimensions modifications.

In the LDL's case, formula (1) is insufficient then. In order to find out the acceptable critical frequencies, necessary became to modify the shaft's geometry in a way that changes one critical frequency, remaining the other one unaffected. By adapting geometry, the 1st critical frequency value can be decreased while the other one remains unchanged (see Figure 9).

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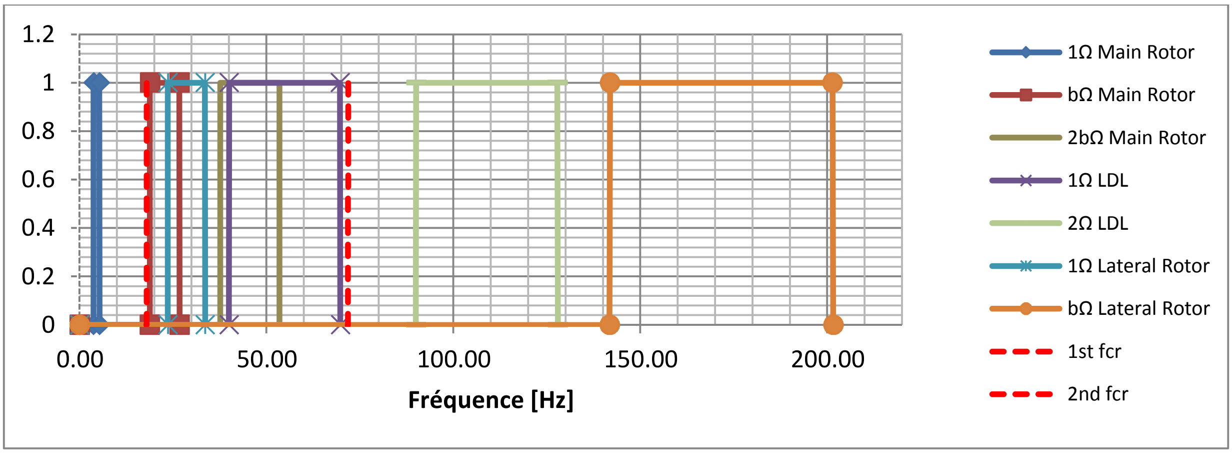

Figure 9: Position of the critical frequencies after the shaft's shape modification

In the second step a shaft's wall thickness has been calculated in order to meet a functional requirement of the load transferring. For this purpose, an internal Airbus Helicopters' methodology supported by many years of company's experience was used. Results show unprofitability of using aluminium as a material for the shaft, thus stainless steel stayed a baseline, what is the non-conventional approach. In accordance with [2] the shaft is classified as potentially impacted by a torsional buckling. It is a phenomenon causes plastic deformation of long cylinders loaded by torsion, while increasing the load. It can occur below ultimate load. A reason of the buckling phenomenon could be a non-linearity of the shaft along its axis. The torsional buckling calculation has been performed and became a dimensioning factor for the tube. Figure 10 shows an example of a tube's torsional buckling damage which was a cause of an accident described in details in [3]. Not enough consideration of the torsional buckling phenomenon would lead to high risk of critical failure of the aircraft.

Figure 10: Torsional buckling failure example [3]

At the end, the flanges have been sized in accordance with an internal Airbus Helicopters' methodology.

As it was stated in the analysis of working conditions (see Table 1), the new way of tube flanges connections had to be deployed. Taking into consideration economical and safety aspects as well as an innovative character of RACER, it was decided to manufacture the flanges and the long tube as a one part creates the LDL's shaft. This result is achievable considering two-level way of manufacturing:

1. Blank shaft- shaped in flow forming process
2. Final shaft- machined from the blank shaft.

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This approach is completely new in the supercritical shafts history. Although a precursor of flow formed shafts was X3's one (RACER predecessor), it was 30% shorter with twice time higher 1st critical frequency (more rigid) than the RACER's shaft, so much easier due to industrialization aspects.

As it was explained in the modal calculations, the shaft has to be shaped in order to obtain critical frequencies in the expected positions. The shape modification has been considered and formed in the flow forming process as well. The LDL's tube is not any more a simple cylinder.

Full process of the blank manufacturing consists in squeezing a raw material, embedded on a cylindrical core, by set of rollers which move along the shaft, while all parts rotate. Reduction of a wall thickness results in increasing of a total blank shaft length. The rollers move only in an area of the core, a free end of the blank moves in an opposite direction than the rollers. The process is finished when the total length of the blank is reached. Figure 11 describes the flow forming process used for the LDL's shaft.

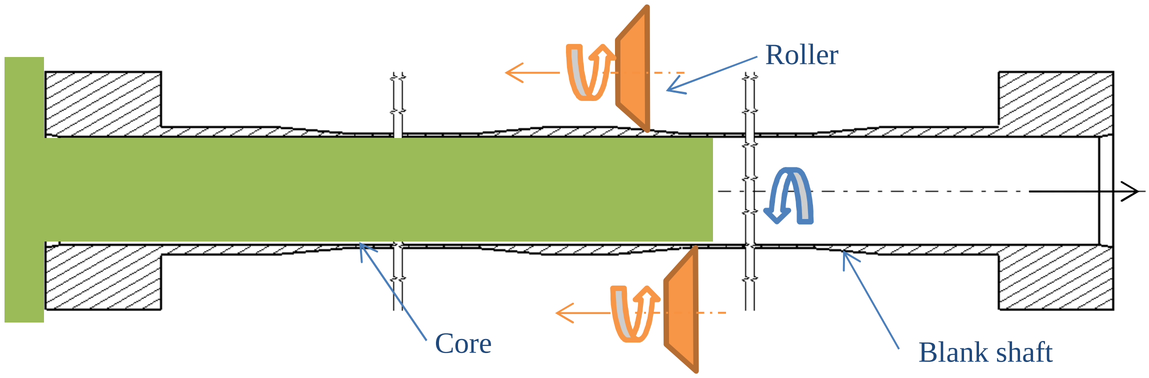

Figure 11: Flow forming process description

Despite a low shaft's static residual deflection, related to the flow forming process, it has to be compensated during the balancing phase.

Before the blank shaft has been manufactured with requested dimensions, several attempts had been made in order to adjust process parameters. It is crucial mainly because there is no parameter, in the process, to set the final blank length. It is a result of initial raw material dimensions and level of material's compression by the rollers for each step. Figure 12 shows material flaking. A root cause was too high feed speed connected with too big thickness reduction in a one sequence. After some parameters adaptation next tests were passed. In Figure 13 test with scale 1:2 model can be seen.

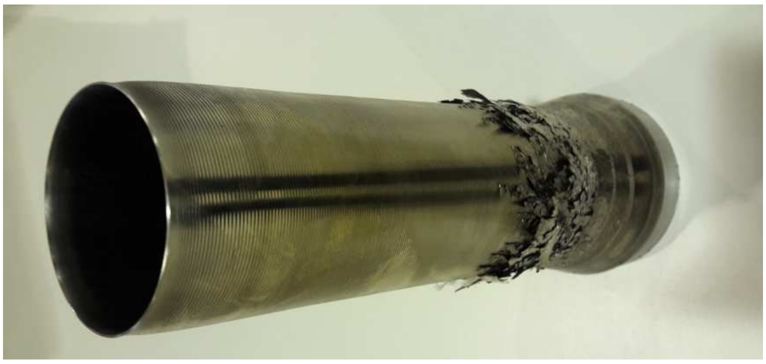

Figure 12: Flow forming test failed

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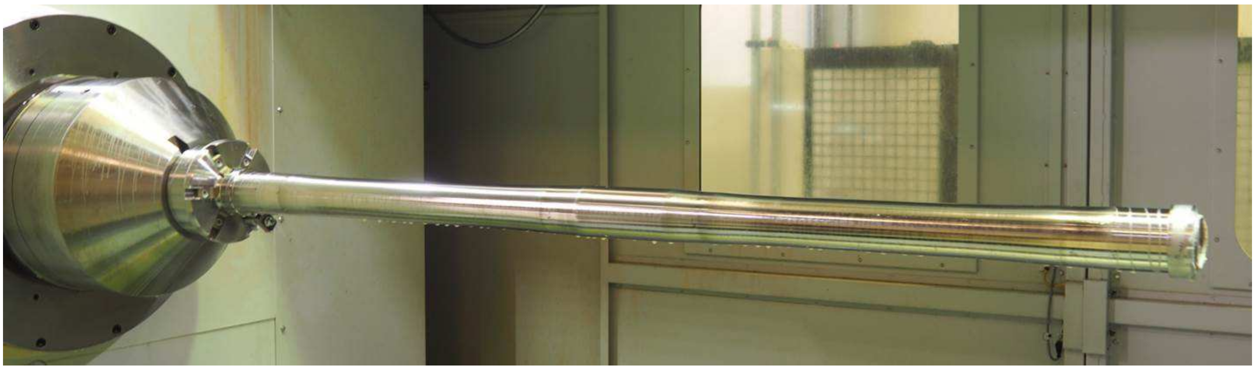

Figure 13: Flow forming test of scale 1:2 passed

In the flow forming process all the most critical areas have been shaped to the final form respecting demanded dimensions. The final machining has been performed on the flanges. Comparing Figure 5 and Figure 14 it can be seen easily how different is the LDL's shaft from the conventional one.

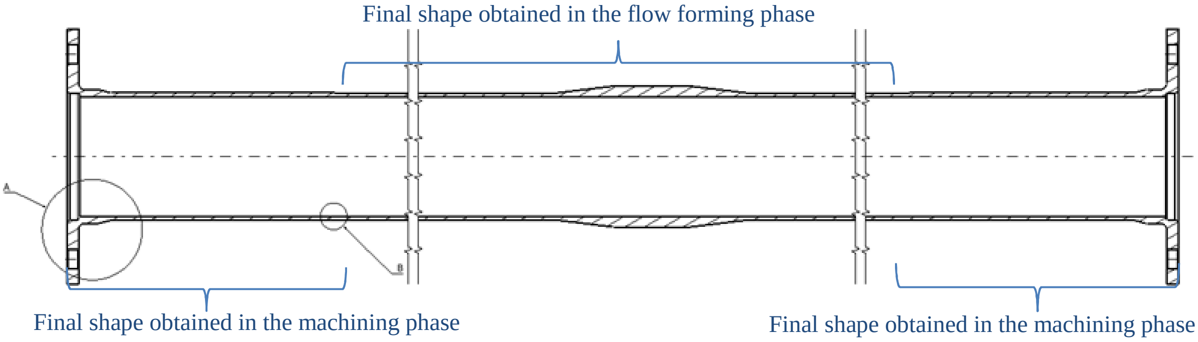

Figure 14: Final shape way of obtaining

After a long and complex process the final shafts are ready to an on ground examination.

Figure 15: LDL's shaft blank

Figure 16: LDL's final shaft machined

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2.3.Soft couplings

The soft couplings form a physical connection between the LDL's shaft and gearboxes. They participate in torque transferring, but apart from it, they compensate all angular displacements and misalignments in relation LDL- environment. Thanks to them, the shaft is loaded by a pure torque and so its weight is lower. A soft coupling concept can be seen in each drive line having the same function as in the LDL. What is very specific to LDL is the order of magnitude of the torque transferred and the load coming from displacement and misalignment, which are 2 times higher than in the conventional drivelines. The traditional driveline's soft coupling are composed of set of shims assembled together (see Figure 17). It is easy in manufacturing and light, but feasibility analysis shows they are not capable to transfer the maximum torque, providing enough softness to cope with all relative deformations in the same time, as requested in the LDL.

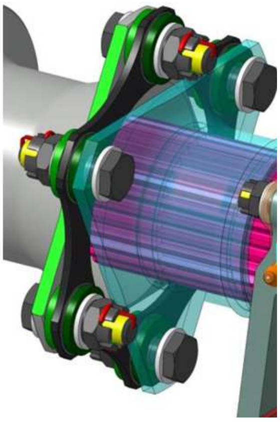

Figure 17: Conventional soft coupling linking two shafts

These extreme conditions force absolutely new approach to the LDL's soft couplings design. The set of thin shims has been replaced by a set of discs with variable wall thickness. The discs are firstly welded between each other, creating couples and then welded with interfaces enabling connection with the other parts (see Figure 18).

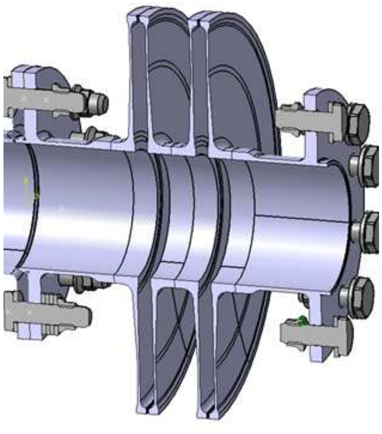

Figure 18: Soft coupling for the LDL

A devoted methodology to find an optimal design of the disc's wall thickness, according to a dedicated multiaxial fatigue criterion, has been deployed in Airbus Helicopters. This kind of soft coupling can be found in high speed shafts (HSS) link engines with main gearboxes. However they are assigned to handle much lower loads. It is visible comparing external dimensions of the HSS's coupling and the LDL's one. The second one is around 55% bigger, and it is the biggest soft coupling ever designed in Airbus Helicopters. In Figure 18, can be seen that the four discs are used in the one soft coupling, and it is the same configuration on both extremities of the shaft. That is a result of a global area calculation algorithm. It takes into account all loads affect the soft couplings and provide a global load spectrum. In the next step the soft

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coupling calculations is executed taking into account the global load spectrum. As an outcome a soft coupling capability to handle the complex load is evaluated. In the last step a wing design is conducted taking into account the soft coupling capability. The wing is a contributor of the soft coupling solicitation. In case of unacceptable results of the wing design, a next step is either to increase amount of the discs of the soft coupling or to redesign the soft couplings, in order to increase their capability. After several calculation loops a trade of between the soft coupling capacity and the wing's design has been found. In Figure 19 an example of the capacity has been presented in a form of an envelope covers combination of the axial and the angular displacement.

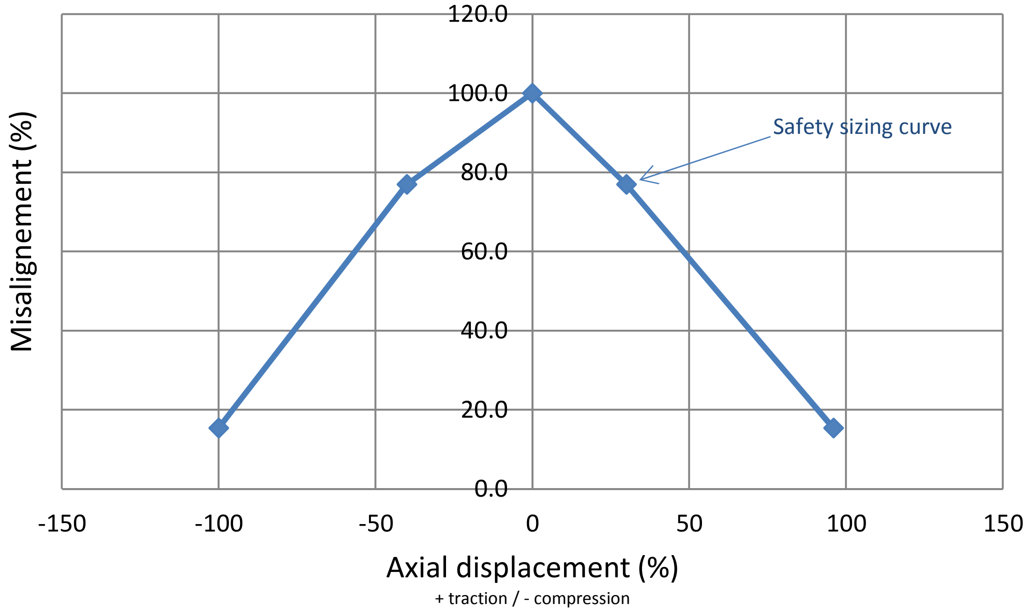

Figure 19: LDL's soft coupling capacity

This type of a close loop algorithm had been never used before. It is mainly because of differences in loads taken by the soft couplings.

As it was mentioned, the LDL's soft couplings are significantly bigger than the other manufactured. This made a big challenge for a manufacturer as well. Due to thin wall of the disc, small deviation of the manufacturing process could lead to unacceptance of the part. The manufacturer developed the mature manufacturing process and currently all parts for development test have been produced and the aircraft's parts production is in progress.

2.4. Friction damper

It is a crucial part of each supercritical driveline. Its main function is to reduce a shaft deflection crossing through the resonance, and to not remain in a constant contact with the shaft beyond the resonance. The principal of the friction damper are described in [4] and a design's concept is presented in [5]. It is featured by low weight and simple design. The alternative solution considered in frames of the LDL was an active magnetic damper's concept described in details in [6]. This is a contactless type of the damper, so does not generate any wear on a shaft surface. From the other side it is a heavier, more complex and requires more space than the friction one, thus the friction damper has been chosen. Referring to Figure 20, the friction damper is composed of the active part 2 squeezed between the fixed part 3 and the moving part 4 by means of an axial force generated by the spring 5. In nominal conditions, between the active part and a shaft 1 is the gap S. When the shaft is crossing resonance, the gap is getting smaller till physical contact between the shaft and the damper. The axial spring's load creates a friction force on the active part, damping the shaft's vibrations.

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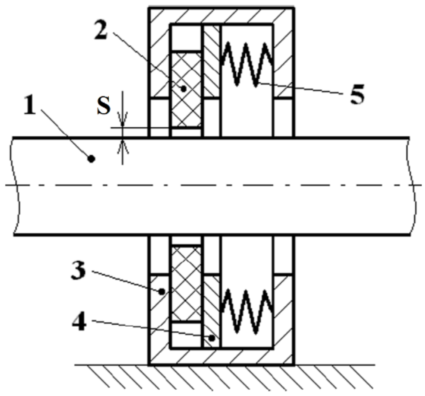

Figure 20: Friction damper- general concept [4]

The principals remain unchanged no matter the conventional supercritical shaft or the LDL is being considered. In the conventional applications the dampers are attached to a fuselage or a tail boom structure (see Figure 2), featured by low relative displacement with respect to the shaft's axis. As showed in Figure 4, LDL's damper is attached to the wing, at a point with the biggest displacement relatively to the LDL. This is the biggest challenge for a designer. In the LDL's configuration the 1st critical frequency is very low while the LDL itself is heavier than the others drivelines. It means that LDL's damping in the resonance can be more difficult than for the conventional drivelines. In this case reasonable is to reduce the gap S (Figure 20) as much as possible. From the other hand, due to the displacement occurring in the area, adequate gap must be provided in order to avoid a constant contact between the shaft and the damper.

In order to meet both requirements several actions have been prepared:

- 5 friction dampers differing in the nominal gap S, have been designed and manufactured;
- A dedicated on ground test will be conducted in order to select a damper providing the best performance;
- Criterion of having no constant contact damper- shaft beyond the resonance is to provide clearance, between the active part 2 and the fixed part 3, while the maximum wing's deflection. This criterion has been implemented in the each damper's design.

2.5.Tests

In the full LDL's development process tests are crucial, in order to proof the logic chosen. The first, preliminary tests have been successfully executed. They confirmed the shaft's critical frequencies and its dynamic behaviour as well as the damper functionality. Figure 21 shows the LDL's preliminary tests installation.

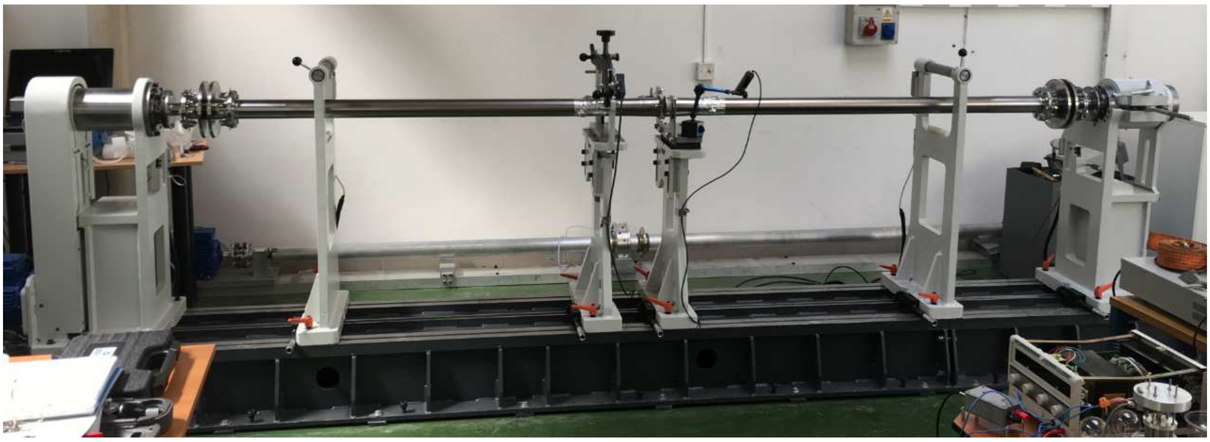
Figure 21: LDL's installation on a test bench

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During the first step, 1st and 2nd LDL's critical frequencies have been checked by means of a bang test. Experimental results presented in Figure 22 are convergent with the analytical ones (see Figure 9)

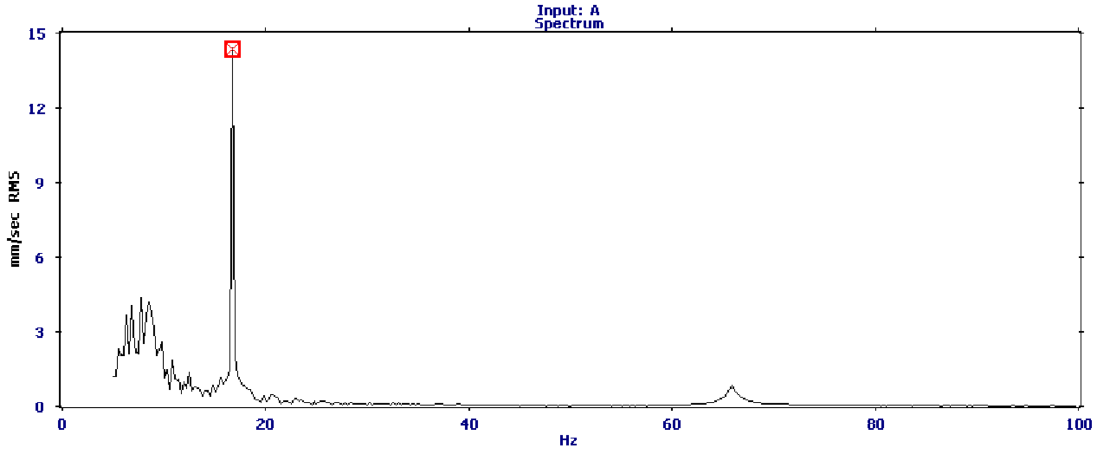

Figure 22: LDL's bang test results- 1st and 2nd critical frequencies

The aim of the second step was to reduce the LDL's deflection near resonance area. It has been done by adding mass, in a place of the maximum deflection. As it can be seen in Figure 23, the preliminary LDL's deflection has been significantly reduced, which enables to cross the 1st critical frequency.

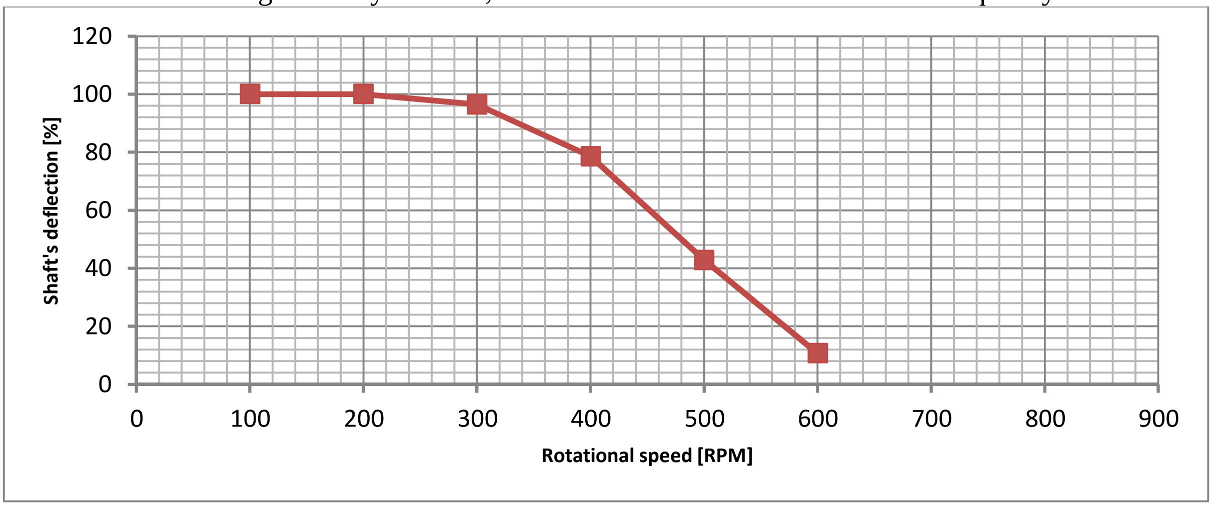

Figure 23: LDL's deflection minimization

Successful third step of the preliminary test demonstrated that the design of the damper, and minimized LDL's deflection, allow to cross the critical frequency with lower displacement than the one expected by calculations (criteria described in 2.4), thus the LDL is able to operate within the space allocation inside the wing.

3. Conclusion

The supercritical drivelines become an encouraging solution for power transmission, mainly due to their low weight and reduced costs. The world leaders, of the rotorcraft industry, are eager to use this solution in their helicopters.

The hybrid high-speed application brings completely new requirements to the supercritical drivelines. The well-known approach has been entirely rebuilt, and pushed the driveline to a new leading edged level, where all "standard" solutions come to be insufficient, thus each development step has been considered from anew, creating a new product the Lateral Driveline.

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4. Notations

f_i: Critical frequency (Hz)
a_i: Coefficient defining a link type on the shaft extremities, unique for each critical frequency
L: Length of a tube (m)
E: Young modulus (Pa)
I: Area moment of inertia (m^4)
ρ: Density kg/m^3
S: Section (m^2)

5. Abbreviations

DoF	Degree of Freedom
HSS	High Speed Shaft
LDL	Lateral Driveline
LGB	Lateral Gearbox
LH	Left Hand side
LR	Lateral Rotor
MGB	Main Gearbox
MR	Main Rotor
RACER	Rapid and Cost-Effective Rotorcraft
RH	Right Hand side
TDL	Tail Driveline
TGB	Tail Gearbox
TR	Tail Rotor

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