# ACTUATION REQUIREMENTS OF AN ACTIVE TENDON CONCEPT IN ROTORCRAFT

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## Abstract

The paper introduces the actuation requirements of an active tendon concept that is being developed under the Horizon 2020 SABRE project (Shape Adaptive Blades for Rotorcraft Efficiency). The basic idea of the concept is to incorporate a tensile structural member (referred to as a tendon) into a rotorcraft blade to introduce a means of controlling the blade's effective stiffness and hence its dynamic properties. This control mechanism should ensure that potentially harmful rotor resonances in various flight regimes are effectively and adaptively avoided. In previous studies, free vibration analysis for the blade-tendon system was conducted numerically and validated against non-rotating experiments. The resulting models are used here to support conceptual design and sizing of the tendon loading system. The actuation requirements in terms of the actuator force, stroke, power and other measures are discussed for simplified representations of the Bo105, Lynx XZ170 and EH101 helicopter rotor blades. It is shown that electro-mechanical linear actuator technology offers realizable loading approach and nominal peak loads of around 6 kN allow adaptive decrease of the in-plane and out-of-plane bending natural frequencies between 0.05/rev and 0.2/rev.

## 1. INTRODUCTION

The rotary wing sector strives towards developing helicopters with increased performance capability and reduced emissions. One way to achieve this is by using shape adaptive blades. Shape Adaptive Blades for Rotorcraft Efficiency (SABRE) is an on-going Horizon 2020 research project which is investigating a number of morphing concepts [1], namely active twist, active chord and active camber. Although each of them has a potential to improve certain aspects of the rotorcraft performance, it is possible that incorporating them in a full-scale blade would lead to dynamic mistuning, associated with resonances. In order to avoid these resonances, it was proposed to develop an active tendon concept which could be used in conjunction with other SABRE concepts.

The basic idea of the active tendon concept is to incorporate a tensile structural member (hereafter referred to as a tendon) into a rotorcraft blade to introduce a means of controlling the blade's effective stiffness and hence its dynamic properties. This control mechanism should eventually ensure that potentially harmful rotor resonances in various flight regimes are effectively and adaptively avoided. The previous studies shown that a blade with the tendon can be modelled either as an axially-loaded beam [2] or a coupled beam-tendon system [3] [4]. Using the latter, it was shown that the natural frequencies of the blade reduce with an increase in the axial load. Using the former, the veering of frequency loci was identified as an important phenomenon in addition to the frequency reduction. Modelling a coupled blade-tendon system (where the tendon is modelled as a taut string and not as an axial force) makes the mathematical description more complicated, but fully represents the behaviour of the system observed experimentally. The previous results, obtained as a part of the SABRE project, showed that Bo105 helicopter can benefit from this concept from a free vibration perspective. This paper explores the actuation requirements of the concept across different blade scales, namely the main rotor blades from Bo105, Lynx XZ170 and EH101 are used. The loading requirement for each of these blades are defined and it is discussed what kind of actuators would be suitable to achieve the required loading. The actuator type, mass, size, energy requirements and resistance to centrifugal force are considered.

The paper is organised as follows: In section 2, the active tendon concept is introduced, three investigated main rotor blades are described, and the components of the active tendon concept are

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discussed in detail. In section 3, the loading requirements for the three blades are described, a possible size and mass of the actuator discussed, and energy and strength requirements are considered.

## 2. ACTIVE TENDON CONCEPT IN ROTORCRAFT

In this section, the active tendon concept is introduced, and the three helicopter blades considered are described.

### 2.1. Active tendon concept

A sketch of the active tendon concept can be seen in Figure 1. It consists of a rotating straight blade which is axially loaded by a tendon. The tendon is attached to the blade's tip, passes through its whole body (parallel to the neutral axis) and is fixed at the rotor hub. The tendon can be theoretically placed in any location of the blade's cross-section [5] or attached in several spanwise locations on the blade [6]. However, in this paper, it is assumed that the tendon coincides with the tensile axis and it is free to vibrate inside the blade. The force is applied to the tendon by an actuator, which has not been considered in previous studies, but will be discussed in this paper.

The free vibration analysis can be performed using a low fidelity model that consists of modified Houbolt-Brooks equations for flapping, lead-lag and torsional motion of the blade, and two wave equations for transversal motion of the tendon [4]. The tendon and the blade are coupled through their connection at the tip. The mathematical formulation and the numerical methods used to conduct free vibration analysis are the same as in previous studies.

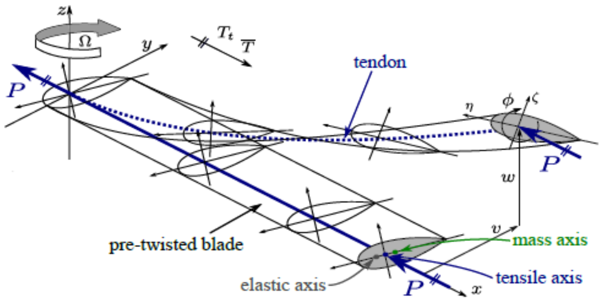

*Figure 1: An active tendon concept: a tendon is incorporated into a blade such that it is attached at the tip, passes freely through the blade and is loaded in or close to the blade root.*

### 2.2. Helicopter blades considered

In this paper, three helicopters were considered, namely Bo105, Lynx XZ170 and EH101.

The Bo105 helicopter is a light, widely used, multi-purpose helicopter deployed in medical services, police, search and rescue, and military missions. The gross mass of the helicopter is 2069 kg and it is designed to carry 4 occupants. The Bo105 features a four-bladed hingeless main rotor and a two-bladed teetering tail rotor. The main rotor blade is considered in this study. The structural blade parameters were extracted from [7] [8] and are summarized in Table 1.

The Lynx XY170 helicopter is a multi-purpose twin-engine military helicopter with a capacity of 8 occupants and a typical gross weight of 2578 kg. The structural blade parameters of its four-bladed main rotor were extracted from [9] [10]. In addition, a lead-lag spring with a stiffness of k/EI = 0.72 was used in the computational model to capture the blade connection to the rotor hub.

The EH101 helicopter is a predecessor of the AW101 and it is a medium-lift helicopter for military and civilian applications. With the capacity of 30 occupants and the gross weight of 10500 kg, it is the largest of the investigated helicopters. The structural blade parameters of one of the blades of its five-bladed main rotor were extracted from [11] [12]. In addition, a lead-lag spring with a stiffness of k/EI = 0.215 was used to capture the blade's boundary condition correctly.

The structural parameters for all three blades can be seen in Table 1, where $m$ is the blade mass per length, $R$ is the blade radius, $R_c$ marks the start of the airfoil profile, $R_0$ is the offset of the blade root from the axis of rotation, $e$ is the distance between the mass and elastic axis, $\beta$ is the pre-twist, $\Omega$ is the rotor speed, $EI_1$ and $EI_2$ are flapping and lead-lag rigidities, respectively, $GJ$ is the torsional rigidity and $EA$ is the axial rigidity.

| | **Bo105** | **Lynx** | **EH101** |
|---|---|---|---|
| $m$ [kgm$^{-1}$] | 7.55 | 7.64 | 12.93 |
| $R$ [m] | 4.91 | 6.4 | 9.3 |
| $R_c$ [m] | 1.03 | 1.81 | 3.11 |
| $R_0$ [m] | 0.38 | 0.80 | 1.30 |
| $e$ [m] | -0.0195 | -0.0047 | -0.022 |
| $\beta$ [rad] | -0.14 | -0.11 | -0.096 |
| Ω [rads$^{-1}$] | 44.5 | 33.3 | 22 |
| $EI_1$ [Nm$^2$] | 6.85e3 | 1.58e4 | 4.16e4 |
| $EI_2$ [Nm$^2$] | 1.7e5 | 2.38e5 | 8.74e5 |
| $GJ$ [Nm$^2$] | 4.37e3 | 5.2e3 | 1.83e4 |
| $EA$ [N] | 6.9e7 | 1.47e8 | 2.22e8 |

*Table 1: Estimated structural blade parameters of Bo105, Lynx and EH101.*

## 2.3. Conceptional design of the active tendon system

The conceptional design of the active tendon concept can be seen in Figure 2. It has four main elements (blade, tendon, actuator and tip attachment fixture) and other optional features, such as tendon attachment or guide tendon points. In the following, each element is described in detail.

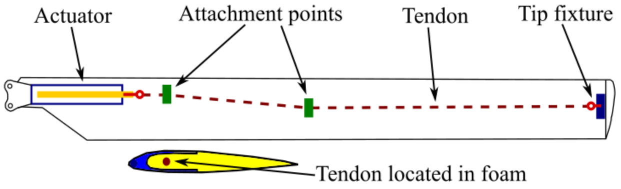

*Figure 2: The design elements of the active tendon concept: the actuator is connected to the tendon which leads through a series of attachment and guide points and is attached to the blade's tip.*

**Blade** – It is assumed that the airfoil of the blade is not affected by the presence of the active tendon. The only notable changes to the blade design are the hollow cavities inside to accommodate the tendon, tip attachment fixture and the actuator.

**Tendon** – The tendon is the essential part of the active tendon concept which delivers the axial load to the tip of the blade. It was also shown in the previous studies [4] that when the tendon can vibrate freely, it can be used as a *tuned vibration absorber*. The tendon is essentially a string or cord stretched between the tip fixture and the actuator. The design and material of the tendon should reflect the blade-specific design requirements. If only the *axial loading for dynamic tuning* is required, the tendon can be a cord of a uniform diameter made of a light and strong material, and tightly embedded in the blade (to permit the axial stretch, but no transversal motion). On the other hand, if an active vibration absorber via the tendon motion is required, the tendon does not have to be a cord of uniform weight, but additional weight(s) may be included in selected place to tune the vibration properties of the tendon, thereby enhancing the active vibration absorber capabilities. The tendon can also be designed to simultaneously deliver the axial force and vibration absorber.

Regardless of the tendon main function, it must be able to handle significant loads, generated by the actuator and centrifugal effects. At the same time, it should be as light as possible. Based on these arguments, the ropes made of Kevlar fibres appear to be suitable candidates.

The cross-sectional location of the tendon is an important parameter to consider because it was shown in [5] that for some positions of the tendon, the natural frequencies can increase as opposed to the current configuration (when the tendon is loaded in the tensile axis) for which the natural frequencies decrease under the applied axial force.

**Tip attachment fixture** – the purpose of the tip attachment is to transmit the force from the tendon to the blade. It was shown in the previous numerical and experimental studies, that the direction in which the force is transmitted to the blade's tip influences the reduction of the natural frequencies of the blade. In an ideal case, the tip fixture remains perpendicular to the blade's tensile axis and the tendon is attached to it in such a way that the axial force can change its direction based on the free motion of the tendon. This will then cause the axial force neither perpendicular to the blade's cross-section, nor tangential to the elastic axis of the blade. Instead, the force will always be tangential to the tendon.

**Attachment and guide points** – While the previously described elements must be present in the proposed design, the attachment and guide points are its optional components. They can be included when there is a need to tune the natural frequencies of the tendon by adjusting its effective inter-segmental lengths or when there is a need to restrict free motion of the tendon. It was shown in [6] that the attachment points can be used to increase the natural frequencies of the tendon so they will be higher than any considered blade's natural frequency. This will mean that the tendon-dominated frequencies do not pollute the frequency range of interest, while at the same time, no vibration absorber capabilities can be achieved. The attachment points can also be used as guides – the tendon does not necessarily have to link the tip and the actuator in a straight manner. Instead, it can adopt varying chordwise and spanwise positions inside the blade. The effect of such guide points has not been studied yet.

**Actuator** – The actuator is an essential element of the active tendon design that generates the loading required for its functionality. In addition to the quantitative requirements defined in the following section, a few qualitative features are expected to be meet by the actuator:

- The actuator needs to allow smooth loading and unloading in the applied loads to provide the full loading and unloading authority.
- The actuator should have design suitable for use in the harsh rotating and vibrating environment.
- The actuator should not require any additional parts or elements external to the blade. The only connection with the hub should be through a power supply and control wiring.
- The actuator should feature the fail-safe load locking capability, thereby allowing to operate the active tendon with an unchanged force for a period of time.
- Force changes are assumed to be gradual and smooth with the load application intervals

reaching several complete rotor revolutions. Unlike many other concepts [13], the active tendon concept is not expected to be actuated multiple times per one rotor revolution.
- The actuator should produce pure axial loading without any parasitic tendon rotation or twisting.

**Safety and maintenance considerations** – The active tendon concept is conceptualised such that it constitutes a secondary safety non-critical load path. Some possible failure modes are discussed here:

(i) **the rupture of the tendon** – The potentially ruptured tendon will stay contained in the blade without compromising its integrity. To avoid the need for the tendon visual inspection a strain-based health monitoring system could be in place to assess the condition of the loading system. The Health and Usage Monitoring System (HUMS) could work similarly to the one developed in [14]. Here, the optical fibre would monitor both the tendon and the blade. The strain measurements could also provide inputs to the tendon actuator control unit.

(ii) **structural instability of the blade** – The blade can lose its stability due to divergence or flutter. The divergence occurs when the tendon-induced axial load exceeds the critical force of the blade. This situation must be avoided because divergence, unlike flutter, cannot be reversed by removing the applied force and would lead to the loss of aircraft. To promote conservatism in the design, the actuator which is not able to deliver the critical loads should be used. As for the flutter instability, which may occur due to aerodynamic effects and it is influenced by the mode shapes and the damping of the blade, the active tendon system must not reduce the nominal flutter stability margins. However, to date, there are no dedicated studies available as to how the active tendon concept impacts the flutter instability [15]. Future studies should carefully investigate if and how the active tendon system influences the aeroelastic properties of the blades.

(iii) **failure of the actuator** – Should the actuator fail, its integrity and behaviour should not impact the nominal blade characteristics. As for the maintenance, the mentioned strain-based HUMS system could be deployed to observe all attributes of the system including the actuator itself.

## 3. ACTUATION REQUIREMENTS

This is a key section of the presented paper where the actuation requirements of the active tendon concept for the three helicopters introduced are discussed. The requirements on the actuator load capacity, size, mass, power, strength and stroke are evaluated.

The sizing philosophy for selecting the actuator is proposed as follows:

1. **Define the required loading capacity** using the magnitude of the force that needs to be generated by the actuator (section 3.1).
2. **Define the required speed of actuation** that is sufficient for the expected active tendon functionality (section 3.2).
3. **Select of the tendon material** by taking into account the magnitude of the force identified in the previous step and other requirements (section 3.3).
4. **Determine required stroke** by considering the axial stretch of the tendon and blade caused by the rotation and the applied forces (section 3.4).
5. **Compute the required power** using the actuation speed and the force required (section 3.5).
6. **Determine the mass of the actuator** based on nominal work of different actuator technologies (section 3.6).
7. **Evaluate the space available for the actuator** by considering approximate dimensions of the blades (section 3.7).
8. **Select the actuator and evaluate its suitability** against the above criteria and literature (section 3.8).

### 3.1. Loading requirements

In order to define loading requirements, the so-called frequency-loading diagrams [4], which show how the natural frequencies of the blade are changed with the applied axial load, are considered. It should be noted that in order to maintain the focus on the modal properties of the blades, the tendon dynamics is omitted in the following analysis. This was achieved by setting the mass of the tendon in the computational model given in [16] to a very small value compared to the mass of the blade. The natural frequencies of the blades that are not loaded by the tendon can be seen in Table 2. This table also contains the critical forces (the axial force due to which the blade loses stability) of each blade. It can be seen from the table that the natural frequencies and mode shapes (indicated by their labels in the brackets) of all three helicopters depend on the specific rotor type while featuring identical mode order and similar frequency tuning.

| | **Bo105** | **Lynx** | **EH101** |
|---|---|---|---|
| 1 (L1) | 0.72 | 0.61 | 0.26 |
| 2 (F1) | 1.11 | 1.17 | 1.19 |
| 3 (F2) | 2.73 | 2.89 | 2.87 |
| 4 (L2) | 4.36 | 3.96 | 3.75 |
| 5 (F3) | 4.81 | 5.27 | 5.24 |

|  |  |  |  |
|---|---|---|---|
| 6 (T1) | 6.31 | 6.26 | 6.55 |
| 7 (F4) | 7.32 | 8.22 | 8.00 |
| $P_{cr}$ [kN] | 39.62 | 44.12 | 63.34 |

*Table 2: Natural frequencies normalised by their respective rotor speed and critical forces of the selected helicopters.*

The frequency-loading diagrams are shown in Figure 3. In these frequency-loading diagrams the effect of the axial force on the natural frequencies of the blade can be clearly seen – the tendon-induced axial force acting through the elastic axis decreases the natural frequencies of the blade. This is the effect that was identified in [2] [4] as the main mechanism which enables resonance avoidance. The tendon-induced axial force should modify the effective dynamic properties of the blade so that its resonances lie away from the rotor harmonics. In this paper, a value of 0.1Ω around each harmonic is considered as a safe margin.

In Fig. 3a it can be seen that the Bo105 blade has higher natural frequencies than the Lynx blade, which in turn, has higher natural frequencies than the EH101 blade. This can be attributed to the different length, rigidities and mass of the blades. However, it should be noted that the order of the modes is the same for all three helicopters, as can also be seen in Table 2. The values of the critical force (the force for which the first frequency drops to zero) are very different for each blade as well, with the EH101 having a significantly larger critical force that the other two helicopters.

With regards to the active tendon concept, it is important to emphasise that the way how the frequencies are influenced by the axial loading is the same for any helicopter regardless of the absolute values of frequencies and forces. This can be seen from Fig 3b where the frequency-loading diagrams are normalised with respect to their own rotor speed and critical force. From this figure, it is clear that, when normalised, the frequency diagrams are very similar and that the rate of frequency decrease is the same for all three helicopters.

The objective of this section is the analysis of the mode sensitivities to the applied loading and identification of the loading regions where all or selected subsets of the modes lie away from the potential places of harmonic excitation. In order to visualize the effect of the applied force without taking into account the values of the natural frequencies, the data from Figure 3 are replotted in Figure 4. In this figure, the tendon-induced axial force is on the x-axis, while the y-axis shows the mode number and its type. The solid lines then indicate the situation where the frequency locus of a given mode is at least 10% away from the potential harmonic excitation.

From this graph, it can be seen that all the helicopters initially operate away from the potential harmonic excitation where no tendon-induced axial load is applied. The exception is the seventh mode of EH101 (the F4 mode) which is close to the rotor harmonics. This is most likely caused by the modelling simplifications and approximations in the used structural parameters and does not present a problem for the following argumentation. Therefore, all the helicopters can be considered as resonance-free when not loaded by the tendon. When the tendon-induced axial force increases the natural frequencies of the blade decrease as seen in Figure 3. Consequently, some of the modes will approach the locations of potential resonant excitation.

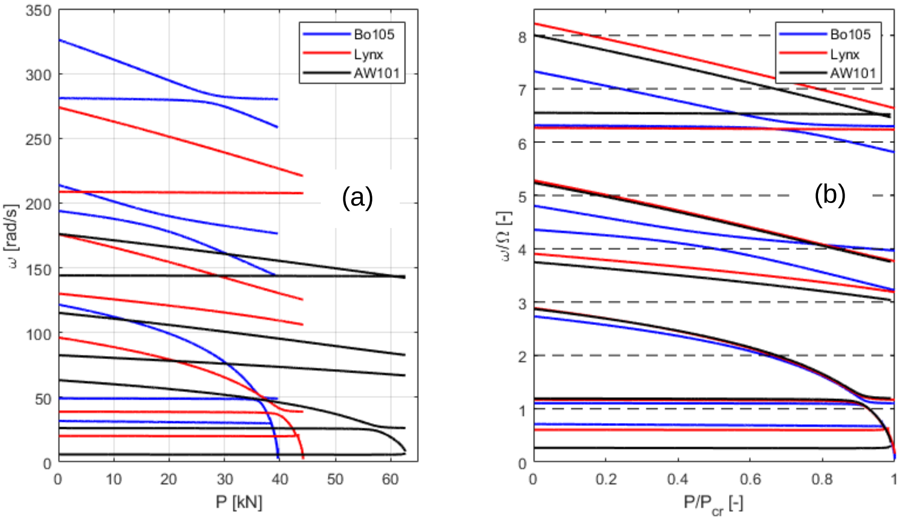

*Figure 3: The frequency-loading diagrams for the selected helicopters: (a) in physical units and (b) normalised by the respective rotor speed and critical forces.*

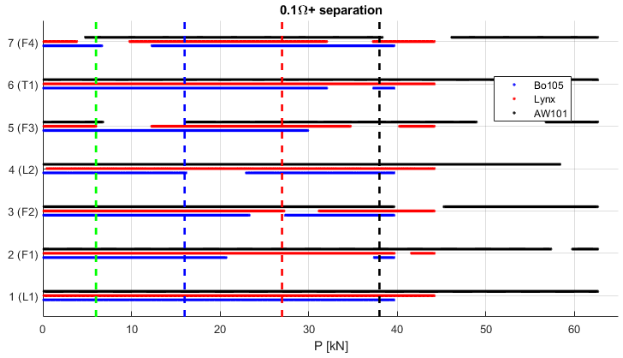

*Figure 4: Separation of natural frequencies and potential harmonic excitation. The solid lines incidate the tendon-induced loading scenaria (on the x-axis) for which the given vibration mode (indicated by the label on the y-axis) is at least 0.1Ω away from the rotor hamronics.*

Therefore, the functionality of the active tendon can be seen as being limited to the region between the nominal natural frequencies of the blade, and the point where one of the main modes approaches one of the rotor harmonics. Interestingly, for the present helicopters, the maximum force defined by this criterion is very similar across all three helicopters. This value is shown in Figure 4 by a dashed green line at 6 kN. In the rest of the paper, this value will be referred to as a “nominal maximal force” and represents the tendon-included axial loading that can be applied to any of the helicopters without one of its natural frequencies approaching the harmonic excitation.

In addition to the nominal maximal force, that is the same for all three helicopter, it is also interesting to note that if some resonances are deemed not to be of high importance (e.g. there are highly damped) the force region of the active tendon may be widened for each helicopter. The limit force under such conditions will be called an “extreme maximum loading”.

Following this approach, for the Bo105, the active tendon can operate between 0 and 16 kN as indicated by the blue dashed line in Figure 4. This however means that the F4 would be excited, which may be of little importance due to damping. The 16 kN limit is given by L2 approaching a rotor harmonics. The second lead-lag mode is known to be of a significant importance for the rotor hub loads and its excitation must therefore be avoided.

A similar argument is possible for the other two helicopters. For Lynx, the extreme maximum loading is equal to 27 kN (assuming F3 and F4 are allowed to be crossed). The extreme maximum loading in this case is determined by the F2 approaching a rotor harmonics. For EH101, the extreme maximum load is 38 kN (indicated by the black dashed line in Figure 4). For this loading, it is assumed that F3 crossing is permitted, while F4 and F2 need to be avoided.

To sum up, two major loading criteria were established. An acceptable loading level, referred to as the nominal maximum force, which allows the active tendon to operate on all three helicopters without introducing resonances. The so-called extreme maximum loading represents the situation when some of the modes are permitted to be crossed and therefore excited. The identified values of these forces will be used to drive the selection of a possible tendon actuator.

In order to show the modal sensitivities resulting from the established limit loads, the data from Figure 3 were replotted in Figure 5 in such a way that an actual decrease in the natural frequencies, relative to the rotor speed, is shown. In Figure 5a), the decrease caused by the nominal maximal force is shown. After applying the 6 kN tendon-induced axial load, some frequencies can be reduced as much as 20% of the rotor speed while none of the considered frequencies approaches the rotor harmonics. In Figure 5b), it can be seen that while the extreme maximum load is

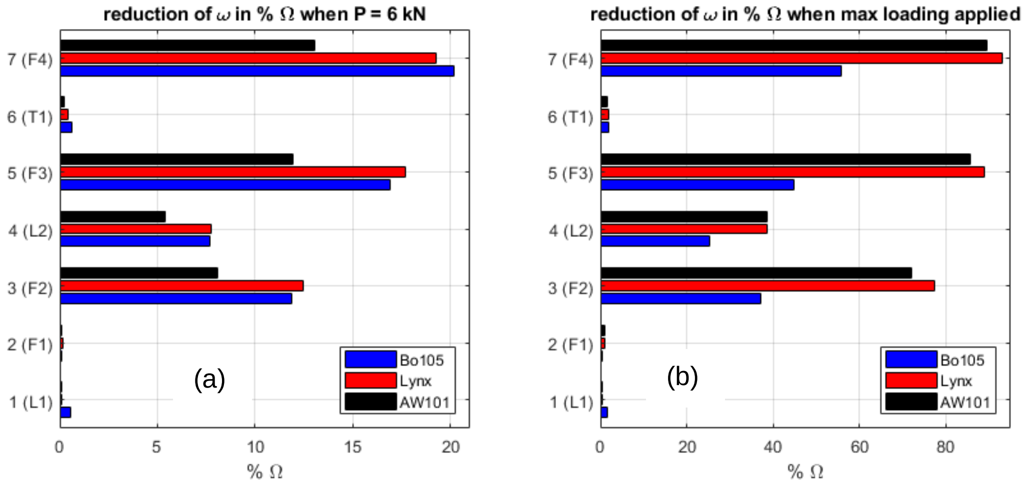

*Figure 5: Reduction of the natural frequencies: (a) nominal maximal force and (b) extreme maximal force.*

applied, some frequencies can be decreased by almost 100% of the nominal rotor speed.

It is interesting to note the resulting differing sensitivities between the studied natural frequencies. It can be noticed that all three helicopters exhibit very similar behaviour. The first two modes – L1 and F1 are very little influenced by the active tendon system. The physical mechanism that causes the insensitivity of these modes for these values of the applied force is unknown. Similarly, the torsional mode is insensitive to the applied load due to the placement of the tendon in the tensile axis, which for all helicopters, coincides with the elastic axis. The fact that L1, T1 and F1 are not influenced by the tendon can be seen as a beneficial feature enabling selective application of the concept. While these modes cannot be influenced, it also means that all other modes' natural frequencies can be significantly varied without changing the natural frequencies of these three modes.

## 3.2. Proposed rate of load application

The speed with which the actuator must be able to provide the required force is an important parameter critical for the proper functionally of the concept. The concrete value is subjected to the exact operational requirement, but some guidelines can be given.

The speed of actuation does not have to be high, because it can be assumed that any required force changes can be gradual and smooth, and that the force adjustments happen only when dynamic properties of the blade need to be altered due to changes in flight conditions. It this highly unlikely the active tendon concept needs to be actuated one or two per revolution as is a common practice in morphing technologies. Moreover, the speed is limited by the Kevlar rope (which should not be loaded by shock) and the fact that the axial load, if applied very quickly, could causes unwanted axial vibration of the blade and/tendon. In addition, the application of the quickly applied axial load in not appropriate with regards to the mathematical modelling used which assumed that the axial load is applied quasi statically, i.e very slowly.

On the other hand, the speed of actuation must be high enough to be able to compensate any dynamic changes that can occur as a consequence of varying blade conditions.

For the purposes of this paper, and in order to provide facilitate the discussion of different helicopter sizes, the speed of actuation is defined such that the concept is fully actuation (form unloaded to maximum applied force) during 10 rotations of the main rotor. This means that the concept must be fully actuated in 1.4 s for Bo105, in 1.8 s for Lynx and in 2.8 s for EH101. The speed of actuator in terms of the speed of its deployment in meter/s is given in section 3.4 where the stroke is computed.

## 3.3. Tendon material selection

The tendon, which is the critical element of the active tendon concept, must be able to safely and reliably transmit the required loading and may even serve as an active vibration absorber as discussed previously in section 2.3. There is a variety of ropes, strings, cords and wires available at the market. In order to select an appropriate type, it is assumed that the tendon is not exposed to any detrimental environmental conditions as it is embedded in the blade, and that it is also loaded slowly and gradually, and no shock loading can occur (the rate of applied load will be discussed further in 3.4) Furthermore, since its operates in the aircraft, it is desirable that it must be as light as possible while providing required strength and maintaining acceptable axial stretch (the strength and elastic axial deflection will be further discussed in section 3.3).

For the purpose of this study, it is assumed that the tendon is a Kevlar cord with the properties given in [18]. The reasons for selection of the Kevlar cord are its low weight and high strength. It should be noted that Kevlar cords are sensitive to shock loading and are not therefore suitable for applications where shock loading is relevant. However, for the active tendon it is assumed that the loading is slow, and all changes in the applied force are smooth. Therefore, no applied axial shock loading on the tendon should occur and the Kevlar cord can be safely used. The properties of the Kevlar cord are density 1.44 kg/m$^3$, Young's modulus E = 140 GPa, elongation at break 3.4% and tensile strength = 3600 MPa [18].

Alternatively, some other non-metallic ropes from [18] could be a suitable candidate. The use of steel lifting ropes or other metallic rope or strings is restricted due to their higher density.

## 3.4. Selection of required stroke

The actuator, of any type, which is placed at the root of the blade will be loaded by a significant centrifugal force that originates from the actuator's own mass, and the mass of the tendon that is attached to it. Moreover, the actuator must be able to provide the required force even when the centrifugal forces cause axial stretch of the blade and the tendon. Therefore, it must have a long enough stroke designed such that allows small, controlled changes to the applied force.

In order to estimate the minimal stroke which the actuator needs to deliver in order to compensate for the axial deflections of the blade and the tendon, it is assumed that the blade and tendon can be treated as an isolated structures that are fixed at one end and free on the other one. They are loaded by the centrifugal and applied axial force and all other bending and torsion can be ignored (in other words, it is assumed there is no coupling between the axial and bending and torsion deflections). The distribution of the axial load can be seen in Figure 6. The blade is loaded by a very high centrifugal forces, compared to the tendon, due to its higher mass and the applied axial load P is acting against the centrifugal force. Therefore, close to the tip, the blade is being compressed while close to the root, the blade is being stretched. The maximal axial loading will however always occur at the root due to a very large centrifugal force. In Figure 6b the axial force distribution in the tendon can be seen. In this case, the centrifugal force magnitude is typically lower than the applied force due to the low mass of the tendon. Moreover, the centrifugal force as well as the applied force stretch the tendon, and there is no place where the tendon is compressed. Similarly to the blade, the maximum axial load, and hence the maximum axial stress, occur at the blade where the tendon is attached to the actuator. It should be noted that in the following calculations the length of the actuator is not considered.

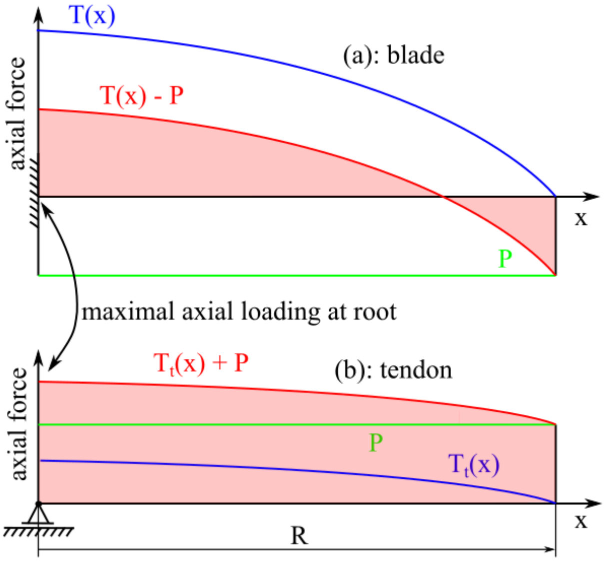

*Figure 6: Distribution of the axial forces for (a) blade, and (b) tendon*

In order to estimate the total axial stretch of the tendon and the blade, the following equation derived from on Hook's law and basic stress and strain relationships is used

$$\delta = \int_{R_0}^{R} \frac{T_t(x) + P}{EA} \mathrm{d}x + \int_{R_0}^{R} \frac{T(x) - P}{EA} \mathrm{d}x \ ,$$

The centrifugal forces acting on the tendon $T_t(x)$ and the blade T(x) are given by

$$T(x) = \Omega^2 \int_{x}^{R} mx\mathrm{d}x \text{ and } T_t(x) = \Omega^2 \int_{x}^{R} m_t x\mathrm{d}x$$

where $m$ and $m_t$ are the mass of the blade and the tendon, respectively. The maximum axial stress in the tendon can be found as

$$\sigma = \frac{T_t(R_0) + P}{A}$$

and occurs at the place where the tendon is connected to the actuator. The maximum stress is not used in the discussion about the actuator requirements, but as a sanity check for the strength of the tendon.

The values of the axial deflections and maximal stresses are given in Table 3 for both the nominal and extreme maximum loading identified in section 3.1. From the table it can be seen that for any applied load, the maximum stress in the tendon does not exceed the tensile strength of the Kevlar cord, and the axial deflection of the tendon and the blade are in order of millimetres, with the maximum of 34.7 mm for the longest EH101 blade. This means that the actuator stroke does not have to be very large.

Conservatively, the stroke of the actuator should be for the practical purposes larger than the obtained values, reflecting the safely factor that accounts for inaccuracies in the estimation of these values and the functionality of the actuator retracted to the fully close and extended position. In this paper, no concrete safely factor is given to maintain the focus on extreme (smallest theoretically possible) values. This will lead to the situation that the power obtained in the following step will be the lower estimate, rather than being subjected to the offset due to the safely factor select in this step.

Based on the obtained minimal stroke and the time of actuation obtained previously, the speed of actuation can be defined. The values, marked by $v_a$, for all three helicopters and both loading states can be seen in Table 3. It can be seen that for the nominal maximum loading, the speed of actuation required for Bo105 is almost twice as high as for Lynx and EH101. On the other hand, for the extreme maximum loading, the speed of actuation for all three helicopters is similar. The highest value of the speed of actuation was obtained for the EH101, but it is still relatively low, just over 12 mm/s.

| | Bo105 | Lynx | EH101 |
|---|---|---|---|
| $T(R_0)$ [kN] | 2.69 | 2.35 | 2.32 |
| $\delta_n$ [mm] | 11 | 8 | 11.4 |
| $v_{an}$ [mm/s] | 7.8 | 4.4 | 4.1 |
| $\sigma_n$ [MPa] | 76.4 | 76.4 | 76.4 |
| $\delta_e$ [mm] | 15.2 | 18.7 | 34.7 |
| $v_{ae}$ [mm/s] | 10.8 | 10.4 | 12.4 |
| $\sigma_e$ [MPa] | 203.8 | 343.8 | 483.9 |

*Table 3: Centrifugal force acting on the actuator and axial deflections of the tendon and tendon.*

### 3.5. Actuator work and power requirements

The work and power requirements of the active tendon concept can be computed based on the proposed speed of actuation and the required magnitude of load. For the computation of the work, it is assumed that the maximum force is applied over the entire stroke, and therefore given by the multiplication of the force and the stroke. This value provides a conservative estimate of the work, because in reality the value of force does not remain constant over the whole stroke due to axial deformation of the tendon. Similarly, the conservative estimates of the power were obtained by multiplying the force with the speed of actuation.

The work and power requirements are summarised in Table 4. It can be seen for the nominal maximum loading, the Bo105 requires more power than the other two helicopters. For the extreme maximum loading, the Bo105 requires the least power while the EH101 the most power.

| | Bo105 | Lynx | EH101 |
|---|---|---|---|
| $W_n$ [J] | 66.2 | 48.5 | 68.4 |
| $P_n$ [W] | 44.1 | 26.6 | 24.3 |
| $W_e$ [J] | 242.2 | 504.9 | 1318.6 |
| $P_e$ [W] | 173.7 | 280.5 | 470.9 |

*Table 4: Work and power requirements*

For comparison, the power of one engine of Bo105 is 350 kW, for Lynx it is 850 kW and for EH101 it is 1560 kW. Therefore, the power required by the actuator in each blade does not exceed 0.1% of one engine power for any helicopter.

### 3.6. Mass of the actuator

When all other parameters of the actuator have been identified, the mass of the actuator can be estimated from the performance indexes defined in [20] and [21] and summarized in Table 5. In particular, the specific work is of interest and will be used in conjunction with the force above to obtain the mass of the actuator which is summarized in Table 6.

| | **Max strain ε [-]** | **Max stress σ [MPa]** | **Specific work W [J/kg]** |
|---|---|---|---|
| Electromechanical | 0.5 | 1 | 300 |
| Hydraulic | 1 | 70 | 35000 |
| Pneumatic | 1 | 0.9 | 1200 |
| SMA | 0.07 | 700 | 4500 |
| Piezoelectric | 0.002 | 9 | 1 |

*Table 5 Actuators parameters based on [20] and [21]*

| | Bo105 | Lynx | EH101 |
|---|---|---|---|
| Electromechanical | 0.22 | 0.16 | 0.23 |
| | 0.81 | 1.68 | 4.39 |
| Hydraulic | 0.002 | 0.001 | 0.002 |
| | 0.007 | 0.014 | 0.037 |
| Pneumatic | 0.055 | 0.04 | 0.057 |
| | 0.2 | 0.42 | 1.098 |
| SMA | 0.015 | 0.01 | 0.0152 |
| | 0.054 | 0.11 | 0.29 |
| Piezoelectric | 66.2 | 48.5 | 68.4 |
| | 242.2 | 504.9 | 1318.6 |

*Table 6: The estimated mass of different actuation technologies: all values are in kg, and the upper number relates to the nominal maximum loading, while the bottom value to the extreme maximum loading*

From this table, it can be seen that the piezoelectric based actuators cannot be used due to their extreme weight. All other actuator types could be theoretically employing based on Table 6, but it must be noted that this mass only represents the mass of the active elements in the actuator, e.g. the fluid in hydraulic based actuators, and does not take into account other elements that may be required. Therefore, the fact that the table says that the hydraulic actuator would have the lowest weight should not be the only decision criterium.

### 3.7. Actuator size

Figure 2 shows that the actuator should be placed in the root section of the blade. It is deemed impractical to place it in the rotor hub. The allowed actuator size will depend mainly on the type of the blade and its nominal geometry. The actuator should be completely integrated inside the blade. In order to estimate the approximate dimensions of the actuator, a cross-sectional dimension obtained from various sources are presented in this section and the maximum allowed dimensions of the actuator are proposed based on them.

For Bo105, based on [17], it can be seen that the blade root part suitable for the actuator is 366 mm long. In addition, from the same reference [17], it can be concluded that the area of the blade immediately following the attachment bolt is 128 mm wide and 50 mm thick. Therefore, as an initial guide, the maximum envelope to incorporate the actuator for Bo105 is: spanwise length 360 mm, chordwise length 120 mm and height 40 mm.

For Lynx, from the drawing given in [11], it can be determined that the blade chord immediately following the main bolt is approximately 0.395 m wide and 0.580 m long. The thickness of the cross-section, only estimated based on the inboard airfoil dimensions, is approximately 50 mm. Therefore, the space available for this actuator is: spanwise length 550 mm, chordwise length 230 mm, height 50 mm.

For EH101, the approximate dimension of this experimental helicopter's blade can be deduced from the drawing in [11], leading to the space available for the actuator with dimensions: spanwise length 1000 mm, chordwise length 300 mm, and height 60 mm.

As already pointed out, these values are treated as the initial dimensional guides to realistically sized tendon actuators. Furthermore, it is plausible to assume that, owing to its relatively weak aerodynamic contribution, this inboard blade segment can be further reinforced to accommodate advanced loading and monitoring system.

## 3.8. Selection of the actuator

So far, the actuation requirements were discussed in this paper, but the type of actuator has not been selected. In this section, it is discussed which kind of actuator would be suitable and why, and then an example of the off-the-shelf actuators is considered and evaluated against the criteria established so far. Five types of actuators will be considered – the electromechanical, hydraulic and pneumatic, smart memory alloys and piezoelectric. Their description can be found in [21].

The piezoelectric actuators are not suitable due to their high mass demands as it was identified in section 3.6. The smart memory alloys are not suitable in cyclic loading due to the need to introduce the heating-cooling cycle. Therefore, they are excluded from further consideration as well. The hydraulic and pneumatic actuators could theoretically be used, but both of them require the pressured fluid which must be contained in a robust containment casing. The presence of the fluid and the weight of the casing makes them unsuitable for the use in the active tendon concept due to centrifugal force and their position in the blade. Therefore, the electromechanical actuators appear to be the most suitable for the active tendon concept. Since they are the most mature technology and there are many designs available, it is likely that even the off-the-shelf solution will meet, or almost meet, the actuation requirements defined in this paper.

Analysis of the existing electromechanical linear actuators identified a large number of companies and suppliers with a wide range of off-the-shelf solutions. For the following comments, actuators such as [22] [23] [24] [25] are used and the considered actuators are shown in Figure 7.

*Figure 7: Examples of considered actuators [22] [23] [24] [25]*

Based on their characteristics it can be said that they are able to provide the required force of 6 kN and required strokes for each helicopter, while their speed of actuation vary significantly between 3 and 17 mm/s. Some actuators are not therefore able to operate with actuator speed as high as the one defined in section 3.2. However, depending on the operational situation, even a lower speed could still be deemed acceptable.

As an example, based on estimates from [22], the weight of the actuator in its 10 kN and 100 mm stroke option is approximately 4.6 kg. Further, from the drawings of the actuators, it can be said that their dimensions are at the limits of the existing blade size envelopes. This means that should similar actuators be used, the blades' root sections would either need to be modified, or actuators and their integration would need to be further customised.

Nevertheless, it can be concluded that while the off-the-shelf solution cannot be directly used for the active tendon concept, their performance characteristics indicate practicality and possibility of achieving the nominal maximal tendon loading. It is important to emphasise that all the criteria used in this paper are conservative estimates and should be treated as preliminary values considered for the actuation design and sizing. In order to design the actuator at the increased fidelity, the definition of the required force and the speed of actuation in section

3.1 and 3.2 must be refined further. Specifically, while the proposed approach is deemed rational, the current conceptual estimates do not reflect any specific operational configuration. Consequently, the relevancy and quality of these estimates will be further improved by investigating the concept in more comprehensive rotor performance setting.

## 4. CONCLUSION

In this paper, the actuation requirements of the active tendon concept evaluated across different rotorcraft blade scales have been defined. It was established that the electro-mechanical linear actuators are suitable candidates to realize the proposed conceptual design. The considered off-the-shelf solutions mostly meet all the defined requirements, but their size can be a limiting factor. However, it should also be emphasised that the reasoning in this paper is mostly based on rough approximations and initial performance estimates that can be significantly improved in the following design iterations. Finally, a general discussion and concept integration strategy is offered rather than a single case study. Therefore, in practice, further actuation development will strongly depend on the specific helicopter and the dynamic tuning requirements which need be achieved by the active tendon.

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