

IN-FLIGHT TUNING SYSTEM FOR THE CH-53G HELICOPTER

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Abstract

Rotor Track and Balance (RT&B) adjustments manually applied to the rotor on the ground are burdensome, error-prone and time-consuming. Moreover, as often as the rotor properties change for any reason the RT&B procedure must be repeated. Today, the search of an acceptable setting usually requires a sequence of several dedicated check flights in different RT&B flight conditions to verify the effect of those manual changes. Due to the flight-condition-dependent effect of blade dissimilarities and due to the limited number of locations where compensational changes can be applied, the suppression of the 1/rev unbalances can never be perfect across all flight regimes. Therefore, a system designed to adjust the RT&B setting during the flight can significantly improve the over-all vibratory condition of the rotorcraft. In addition, such system considerably reduces the time for RT&B still required today for the repetitive check flights and the manual adjustments.

ZF Luftfahrttechnik had been contracted to demonstrate the feasibility of this approach within a dedicated flight test campaign. Core components of the In-Flight Tuning (IFT) system are electrical Smart Pitch Rods (SPR™), which replace the rigid pitch links of each blade. The SPR™s change their length upon digital commands received from a dedicated control computer. Such close-to-production IFT system has been installed onto a CH-53G testbed of the German Armed Forces and was flight tested at the German Military Flight Test Center in Manching. The tests were designed to prove the concept in a realistic environment and have successfully proven autonomous IFT operation based upon adaptive closed loop algorithms.

The benefits that were demonstrated during this campaign comprise (1) reduced vibrations compared to the reference case with fixed pitch link settings throughout all flight regimes, (2) compensation of degrading RT&B condition over time, (3) automatic reconfiguration after sudden changes of blade properties, and (4) reduced RT&B effort after initial rotor reassembly, blade exchange and/or control system rigging. It could also be shown that the IFT algorithm was convergent and robust throughout all maneuvers and never lost track even during the most agile flight condition changes.

1. NOTATION

ACU	Actuator Control Unit
COTS	Commercial off-the-shelf
DAL	Design Assurance Level
FH	Flight Hour
FOD	Foreign Object Damage
GSE	Ground Support Equipment
IBC	Individual Blade Control
IFT	In-Flight Tuning
LF	Level Flight
MRlat [ips]	Lateral main rotor vibration, component measured at the upper housing of the main gearbox
MRvert [ips]	Vertical main rotor vibration, component measured in the nose avionics bay [inch per second]

nR ...	n/rev component of ...
Pos	Position
RT&B	Rotor Track and Balance
SPR™	Smart Pitch Rod
ZFL	ZF Luftfahrttechnik GmbH

2. INTRODUCTION

2.1. Motivation

Manual Rotor Track and Balance (RT&B) adjustments to be applied on the ground are burdensome, error-prone and time-consuming. As soon as the rotor properties change for any reason (water ingress, erosion, blade change, etc.) the RT&B procedure must be repeated in order to restore the required overall RT&B condition. Today, the search for an acceptable setting usually requires a sequence of several dedicated check flights to

verify the effect of those manual changes in different RT&B flight conditions.

The traditional RT&B procedure aims to establish a condition in which the rotor exhibits the lowest overall 1/rev vibrations despite any inherent mechanical and aerodynamic blade dissimilarities. However, the multiple sources of blade dissimilarities cannot be compensated through simple local changes such as added masses or bent tabs. Due to the flight-condition-dependent effect of such dissimilarities and due to the limited number of locations where the compensational changes can be applied, the suppression of the 1/rev unbalances can never be perfect across all flight regimes. Therefore, a dedicated provision designed to adjust the pitch link lengths during the flight can largely improve the overall vibratory condition of the rotorcraft. In addition, such system would considerably reduce the time required today for the repetitive RT&B check flights and the manual adjustments.

During a joint Individual Blade Control (IBC) wind tunnel test campaign in the National Full-Scale Aerodynamic Complex (NFAC) at Ames, ZFL was able to prove this concept by using flight condition dependent pitch angle settings introduced by the experimental IBC system, see [5]. The blade root adjustments alone were able to compensate not only wrong pitch link lengths but also inertial unbalances and misaligned tabs. Figure 1 shows a typical result recorded during that campaign.

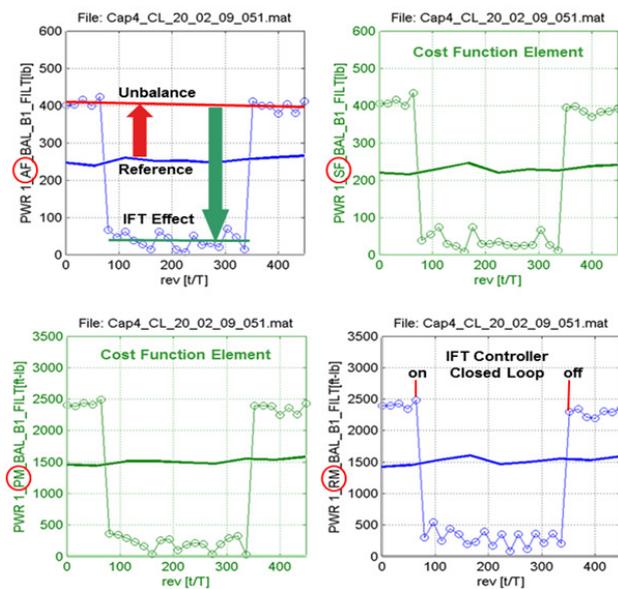


Figure 1: Compensation of increased 1/rev vibrations due to experimentally removed hub balance weight through closed loop IFT (aft/side force, pitch/roll moment)

A deliberately seeded mechanical unbalance, which had considerably increased the vibrations in all observed rotor balance axes, could be more than compensated by blade-individual pitch changes commanded in real-time by the closed loop IFT controller and mechanically introduced by the installed IBC system.

2.2. Proof of Technical Solution

Although it is not trivial to move trim masses or change the trim tab setting in flight, it is comparably straightforward to adjust the pitch link length by some sort of electrical actuation in order to provide the above mentioned In-Flight Tuning adjustments. Based on the promising wind tunnel test results, ZF Luftfahrttechnik was contracted to demonstrate the feasibility of this approach within a flight test campaign.

Core components of the developed In-Flight Tuning (IFT) system are six purely electrical Smart Pitch Rods (SPRTM), which replace the rigid pitch links at each blade, see Figure 2. The SPRTMs contain electro-mechanical drive elements as well as electronic hardware to control the pitch link length upon digital commands sent by a dedicated control computer. The respective software is designed not only to improve the traditional RT&B process but also to provide autonomous reconfiguration capabilities. A close-to-production IFT system has been installed onto a CH-53G testbed of the German Armed Forces and was flight tested at the German Military Flight Test Center in Manching. The tests were designed to prove the concept in a realistic environment and have successfully demonstrated autonomous IFT operation based upon adaptive closed loop algorithms.

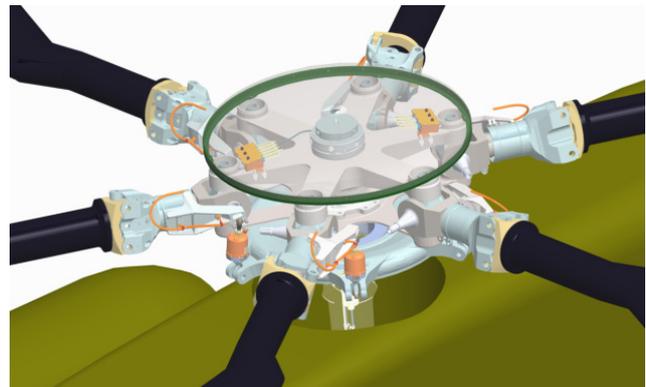


Figure 2: IFT System with SPRTMs mounted onto CH-53G rotor head

3. IFT SYSTEM

3.1. System Layout

The system layout follows the approach to re-use existing RT&B equipment where possible and useful. Thus, several components are based upon COTS RT&B equipment designed and manufactured by Helitune Ltd. and used worldwide across a broad range of rotorcraft types. A detailed description of the different components and their interaction can be found in [5] and [6].

The overall system architecture of the IFT production system is shown in Figure 3. The system consists of some adapted COTS components as well as several newly developed units. The greenish colored elements are GSE-type components only used during the Return-to-Service flight that will replace the traditional RT&B procedure. The setup used for the flight tests was very similar, however for maximum flexibility the IFT algorithm was running on a separate dSPACE computer connected to the IFT Commander.

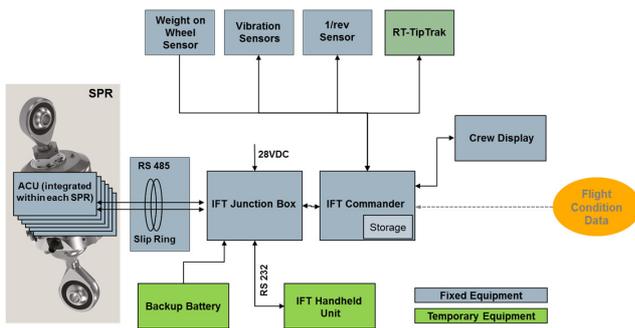


Figure 3: System Architecture of IFT System (production configuration)

The SPR™ as shown in Figure 4 replaces the original fixed-length pitch link of the helicopter. It acts as an electro-mechanical actuator, which provides the capability to adjust the length of the pitch link with an authority, adjustment speed, and load capability suitable for the application to the CH-53G helicopter. Within the housing of the SPR™ also resides an autonomous Actuator Control Unit, which provides position measurement and control, health monitoring, as well as the power electronics to drive the brushless DC motor.

The IFT authority is deliberately restricted to a range which prevents any system failure to produce a potentially unsafe condition. For the CH-53G this in-flight authority was set to approximately 0.4 deg

blade pitch angle which corresponds to 10 clicks in terms of the CH-53-specific adjustment unit. Based on this approach, the requirements for the software design could be kept at a reasonable level. For the core IFT components DAL D with several DAL C enhancements according to RTCA DO-178B was applied and sufficient for certification.

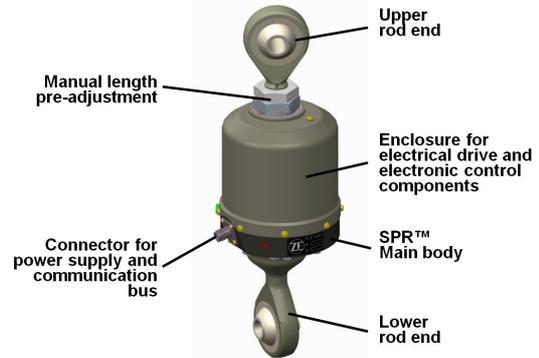


Figure 4: 3D rendering of the SPR™ designed for CH-53G helicopter

Besides the in-flight adjustment feature within the safely limited authority, the length of each SPR™ can also be commanded to electrically travel within the full range as might be required for rigging on the ground. In that case, the authority-restricting hard stops can first be disengaged and later reactivated.



Figure 5: Production variants of IFT avionic hardware provided by Helitune Ltd.

Further elements of the IFT system are depicted in Figure 5. They have been developed and manufactured by Helitune Ltd., the company specialized in RT&B hard- and software. The blade-individual pitch control commands are continuously computed in real-time within the IFT Commander by a ZFL-proprietary algorithm. They are then routed along with the required electrical power via a dedicated slinging to the SPR™s. The data are transferred by a digital RS485 bus for which a

protocol according to SAE RITA AS5394 had been defined. For the sparse interaction with the flight crew the system features a small Crew Display that signals the current system status, allows pausing the closed loop control or adding event markers and can indicate certain post flight messages.

Beside those components that remain permanently installed, the so-called IFT HandHeld Unit is used to support the RT&B process. While still on board throughout the test flights, in the production version this component serves as the primary user interface only for the Return-to-Service phase. The operator will be guided along all required steps from the preparation through the Return-to-Service flight to the final pre-adjustments of the SPRTMs to their optimum default positions.

3.2. Aircraft Integration

The rotor head installation of the SPRTM actuators as realized with the testbed aircraft is shown in Figure 6. Two small power and data distribution boxes were mounted invisibly under the hub cap. All vibration sensors are installed at the traditional RT&B locations in the fixed frame, because it was understood that they had carefully been selected to reflect the over-all vibratory condition of this particular aircraft.



Figure 6: CH-53G IFT System with SPRTMs installed between swashplate and pitch horn

Although the concept of IFT puts the focus onto the tuning or vibration minimizing aspect (n.b. the T of IFT stands for Tuning rather than for Tracking), Helitune's optical tracker RT-TipTrak can be connected to the system to monitor the blade positions as required at least for the Return-to-Service flight. During the flight tests the camera was permanently mounted in the nose section of the aircraft to as shown in Figure 7. Many more details relating to the technical specification, the specific flight test setup, the qualification on component and system level as well as the performed certification steps can be found in [1].

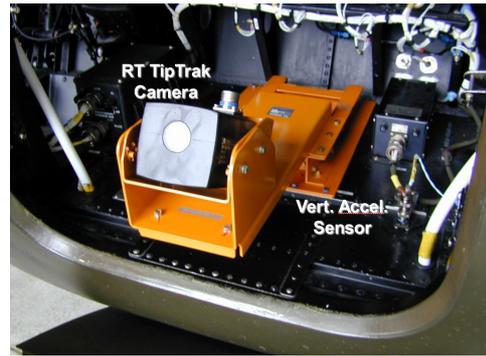


Figure 7: Helitune RT TipTrak optical tracker and vertical acceleration sensor in nose avionics bay

4. IFT FLIGHT TESTS

4.1. Overview

The flight tests were started with some dedicated certification flights to validate the system behavior and performance. These flights comprised tests with respect to EMC, aircraft reactions on erratic or worst case pitch settings, SPRTM drift under extreme loads and potential interactions with the existing AFCS. All tests were passed without any issue. Figure 8 shows the testbed aircraft during one of the early certification flights.



[Photograph Courtesy of Alex Beck]

Figure 8: CH-53G testbed 84+94 during an IFT test flight

In the next step the functionalities of the control algorithms were checked in manual and automatic mode. Since the system always performed as expected, it was possible to immediately progress to the closed loop control test flights. The campaign stretched out over 44 FH and was completed in June 2014. Due to the flawless operation of the IFT system, it was possible to let the pilots propose their own missions towards the end of the tests to further consolidate the grown confidence in the system performance.

4.2. Test Results

As mentioned, during the very first phase of the test flights, the SPRTMs were controlled in open loop manner. Predefined input patterns were called up and the impact on the different harmonic vibratory components was recorded. Although the primary focus was put on the 1/rev component, all other harmonics and the blade tip path were continuously monitored to prevent any unnoticed occurrence of unwanted side effects. The usable SPRTM stroke was arbitrarily mapped to the interval between 10 and 20 clicks. Therefore, the middle position corresponds to an absolute setting of 15 clicks at each blade, which is used as the initial setting ("Default Position") around which positive or negative excursions of maximal 5 clicks could be commanded.

Figure 9 shows the typical reaction of the 1/rev vibrations in ips plotted in polar format. As in the remaining part of this paper, the data shown are taken from the two sensor locations used for today's main rotor RT&B (upper housing of main gearbox and nose avionics bay). In this example the SPRTMs at two opposite blades have been commanded to travel first by 2.5 and then by 5 clicks into opposite directions. The traces show all instantaneous measurements over the complete cycle from fading in, resting at the defined position and returning to the Default Position. The behavior is basically linear and the measurements are consistent and repeatable. The extraction of stable and usable data is much more challenging in hover than in forward flight. Therefore, some sophisticated conditioning and filtering had to be applied to the raw data to provide reliable real time input for the closed loop control algorithm.

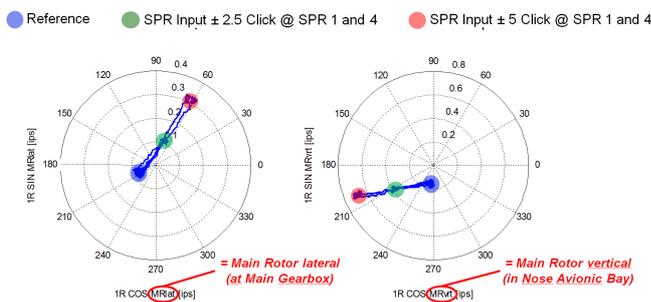


Figure 9: Effect of ± 2.5 and ± 5 click SPRTM displacements simultaneously applied to opposite blades on 1/rev lateral and longitudinal vibrations, LF @ 130 kts

The full advantage of the active pitch link is rooted in the capability to apply in-flight changes to the pitch settings. As will be shown below, the optimum

settings do differ from one flight condition to the other and therefore a continuous re-adjustment is required to maintain the desired level of minimum vibrations. Obviously, no human operator is able to manually change the commanded values in a suitable manner. Thus, from the beginning IFT was conceived as a function that needs to be implemented by a self-contained system which autonomously computes and applies the optimum settings.

The high level control system structure had been derived from an architecture that was developed for the past IBC flight tests as described in [4]. The vibration signals are sampled and buffered at a fixed rate and then resampled based on the actual 1/rev signal. Subsequently, the data are transformed into the frequency domain by discrete FOURIER transformation to extract the relevant rotor harmonics. Due to significant fluctuations of the measured accelerations and low frequency disturbances related to the aircraft flight mechanics, careful filtering and averaging has to be applied to provide suitable input signals for the control algorithm.

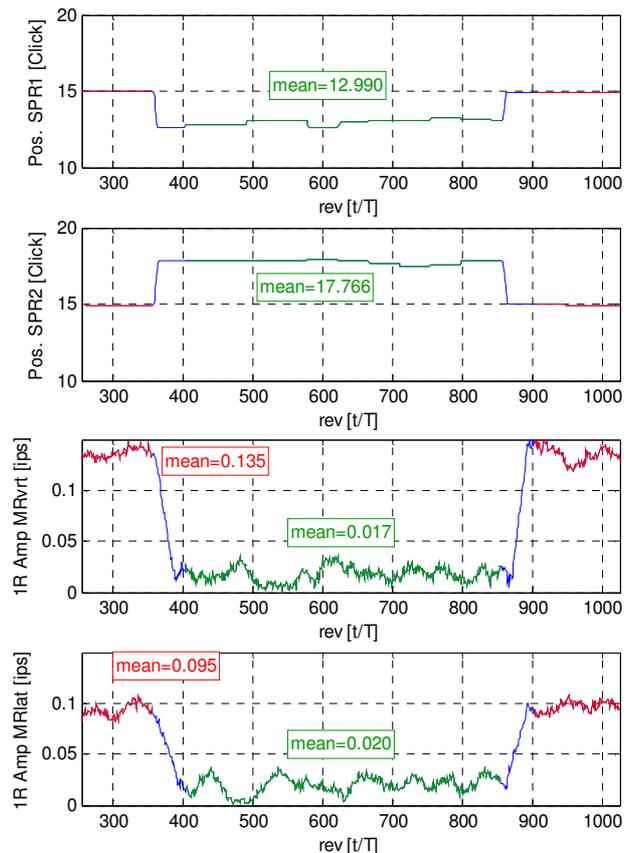


Figure 10: Closed loop control sequence (IFT off – IFT active – IFT off) top: SPRTM positions, bottom: 1/rev vibrations, (two blades controlled, LF @ 110 kts)

An example for the quality of the controller is provided by Figure 10, which shows time histories of a closed loop control sequence recorded in level flight at 110 kts. Whereas the upper two diagrams of the figure provide the pitch settings applied by the two controlled SPRTMs, the lower two diagrams show the magnitude of the two processed vibration signals MR lat and MR vert. The red sections represent the reference measurements with the IFT controller disabled and the SPRTMs set to their Default Position. The blue sections show the transients after the controller has been switched on or off, respectively. In between resides the time window with the IFT controller actively commanding pitch changes (green). The blue transients clearly indicate how quickly the vibration components are reduced. But it also becomes clear that even during the comparably short period of less than three minutes the controller needs to visibly re-adjust the settings to maintain the minimum vibration level.

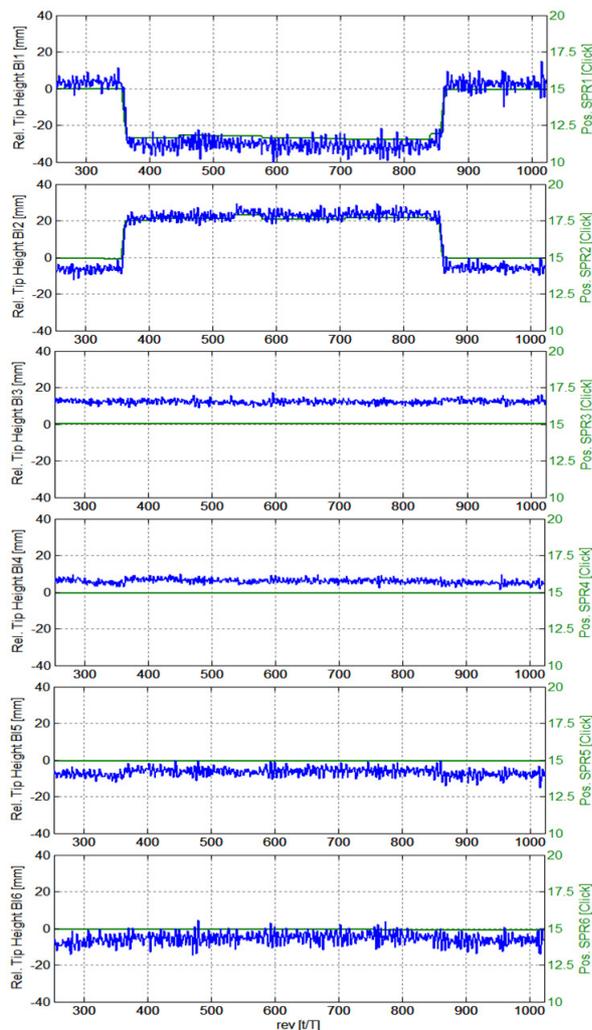


Figure 11: Example of optically measured blade tip heights during closed loop control sequence (level flight @ 110 kts)

Although the initial condition would have already been judged more than sufficient by the existing RT&B standards and was fully conforming to the limits given by the maintenance manual, the additional reduction of the vibratory components was better than 75% for this level flight condition.

Figure 11 shows the corresponding blade heights as recorded by the TipTrak camera. It can clearly be recognized that for this particular flight condition enforcing flat track with all blades flying at close to zero deviation from the mean value would not have improved the vibratory condition. Considerable deviations were actually needed to optimize the vibration level. This underlines the fact that with an active system flat track is not anymore a usefull precondition for a smooth rotor as it might be for the traditional fixed setting.

4.2.1. In-Flight Adjustments for Flight Condition Dependent Optimization

The closed loop controller was then used to automatically command the SPRTMs to positions that would minimize the 1/rev vibrations during different flight conditions. Beside the variation of the forward speed, which is presented here, tests have also been conducted at different loading and CG conditions as well as in different altitudes. Figures 12 and 13 show for two separate flights (8 and 9) the respective comparisons between the reference vibration levels with the SPRTMs set to the default position (red) and the levels after re-adjustment as commanded by the IFT controller (green).

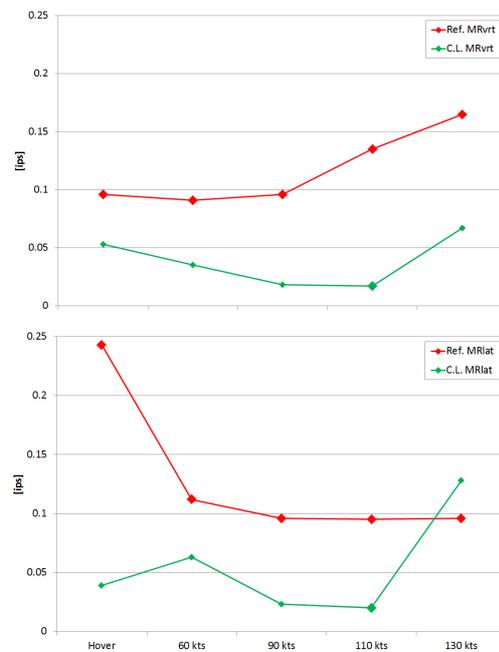


Figure 12: 1/rev vibration reduction due to flight condition dependent closed loop SPRTM adjustments (top: MR vert, bottom: MR lat; flight 8)

Measurements have been taken across the full flight speed range. As can be seen, the IFT system consistently succeeds in reducing the vibrations by approximately 70% on average. Only at maximum speed the effect is somewhat smaller. Since both vibration components MR vert and MR lat were equally weighted in the quadratic cost function, in one case the controller has traded a small degradation of the already low component against a larger reduction at the higher level. There was not one single case in which the fixed setting would have yielded better results than the IFT solution.

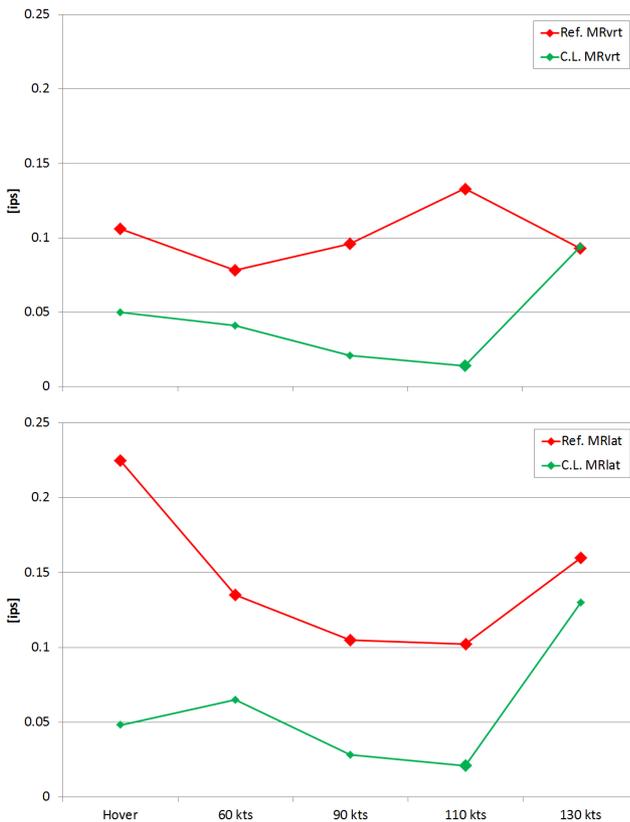


Figure 13: 1/rev vibration reduction due to flight condition dependent closed loop SPRTM adjustments (top: MR vert, bottom: MR lat; flight 9)

Figure 14 shows the corresponding adjustments at the two activated SPRTMs that were commanded by the controller to achieve the shown reductions. As it had already been observed during the wind tunnel experiments [5] it becomes obvious again, that as soon as the rotor is not perfectly symmetric anymore and the blades have not exactly the same properties there is no constant setting that can provide minimum vibrations across all flight conditions. Moreover, it is interesting to notice that the required pitch changes do not only differ from one flight speed to the other, but look significantly different for the two separate flights, too.

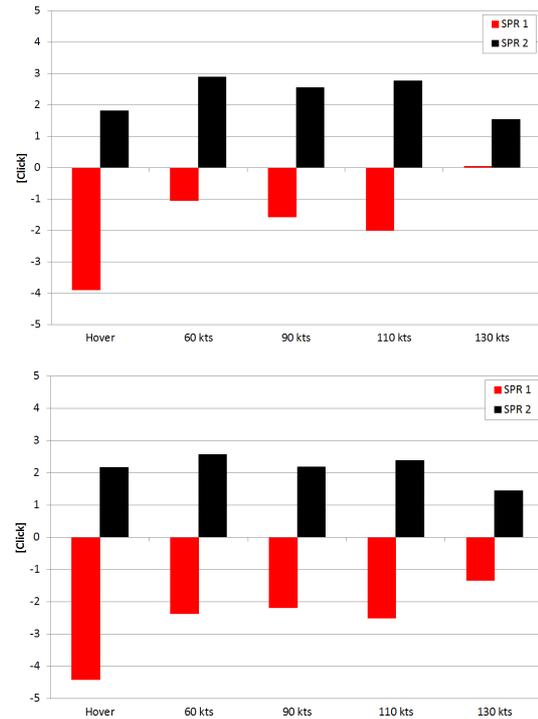


Figure 14: Adjustments of SPRTM red and black as computed by the closed loop controller to minimize 1/rev vibrations (top: flight 8, bottom: 9)

4.2.2. Compensation of Creeping Blade Changes

Interestingly enough, at some point it was noticed that during the course of the flight test program the reference values had changed extensively. Due to limited resources and mandatory changes to the testbed aircraft (unrelated to its RT&B condition), there was a four month gap between the first reference and RT&B check flight and the start of the actual IFT test flights. The initial measurements had shown moderate but noticeable 1/rev levels, which was considered a useful starting point, since it was intended to show the capability of the IFT system. When the flight tests were resumed after that brake, however, the reference vibrations had fallen to much smaller levels for the same SPRTM defaults settings. This finding is underlined by Figure 15 and corresponds to the experience of the operator as well as to statistical data from the traditional RT&B activities.

As a result of the creeping changes, the reference values were sometimes smaller than desired and consequently the IFT benefit was somewhat less impressive as it could have been. It is also interesting to notice that the impact of the elapsed time (along with the change of the meteorological conditions for instance) seems to be stronger than the influence of the number of flight hours.

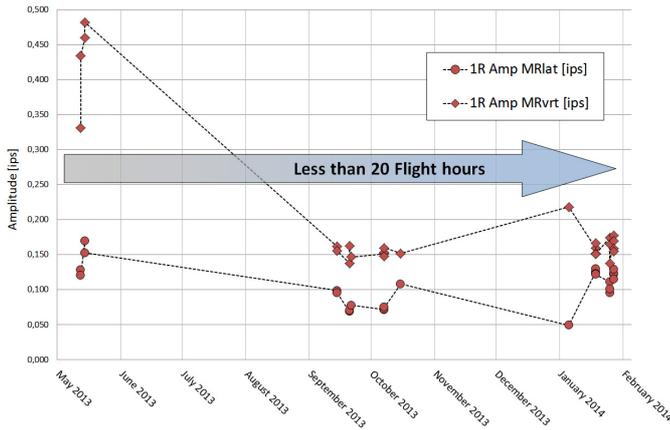


Figure 15: Drift of reference vibrations during the course of a 8+ months 20 FH test flight period (LF @ 130 kts)

4.2.3. Compensation of Tab Misalignments

One important benefit of IFT, which had already been demonstrated during the wind tunnel tests [5], is the option to waive any laborious tab adjustments in favor of the automated but (n.b.!) flight condition dependent blade root pitch adjustments through IFT. Figure 16 shows time histories of a closed loop flight after the tabs of blades 5 and 6 had been bent by +10 mills each. This deliberate manipulation has driven the vibration levels beyond the standard limits for the vertical axis. The mean values of the reference vibration levels recorded before the tab setting had been changed are marked by the red dashed lines. As can clearly be seen, the tab effect could not only be neutralized by IFT but the residual vibration levels with closed loop control active were appreciably smaller than before the tab bending.

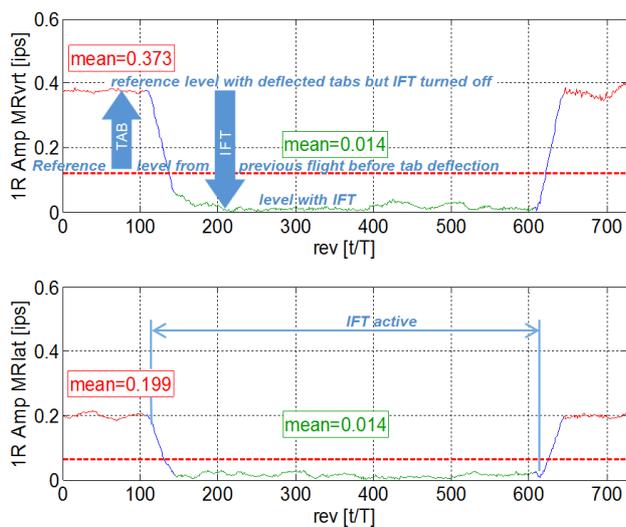


Figure 16: Compensation of 1/rev vibrations from two intentionally deflected trim tabs (+10 mills each) through in-flight pitch adjustments, LF @ 90 kts

The corresponding SPR™ positions are presented in Figure 17. In this case all six SPR™s were commanded and used for compensation. To lower the required travel compared to the case when only two SPR™s are used a special apportionment algorithm can be activated to redistribute the computed solution across all blades, see chapter 4.2.5. Thereby the computed settings stayed within the available authority for all individual SPR™s.

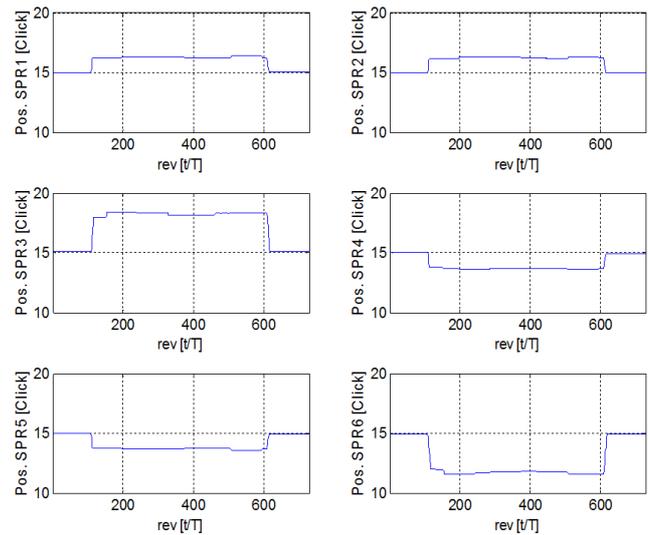


Figure 17: SPR™ positions computed and applied to compensate the deliberate trim tab deflection (two blades +10 mills each, level flight 90 kts)

The next two figures once more underline the impact of the flight condition. Figure 18 shows the vibration levels for the reference case, the effect of the bent tabs, and the successful compensation through IFT. It should be noted that the vibratory condition after the tab manipulation was well above the permissible limits in all flight conditions and the aircraft could not have been released for flight.

Figure 19 provides the corresponding SPR™ positions commanded to achieve the shown vibration reduction. Once more it is obvious that no fixed setting exists, which would have accomplish this successful compensation across the whole speed range. Only the introduction of flight condition dependent settings allows completely removing of the tab effect and even undercutting the reference levels.

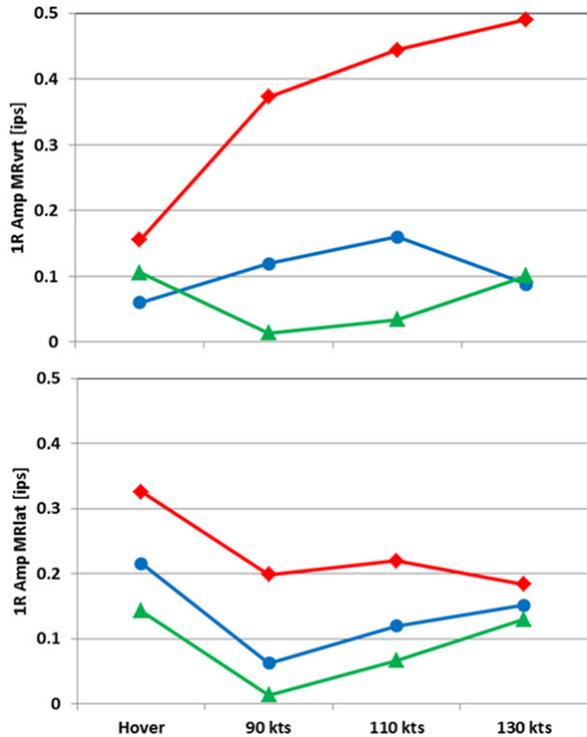


Figure 18: Compensation of 1/rev vibrations from intentionally deflected trim tabs through flight condition dependent pitch adjustments

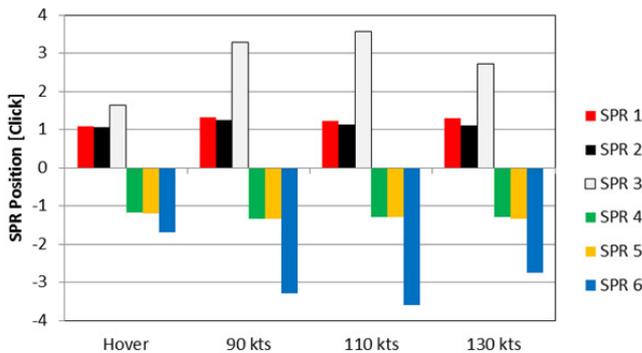


Figure 19: Flight condition dependent SPR™ positions as applied to compensate the deliberate trim tab deflection

4.2.4. Compensation of Blade Dissimilarities (by FOD, Blade Exchange, ...)

Especially for military operators but also for other potential customers, the capability to counteract sudden changes of the blade properties is highly valued and considered a strong benefit of the IFT system. Blade changes can be caused by different types of spontaneous or externally provoked structural failures but also by FOD or battle damage through hostile fire.

During prior simulations it had already been predicted that considerable differences in the blade properties could be compensated by suitable re-adjustments of the pitch settings. In those cases the goal would certainly not be to restore a perfect smooth RT&B condition but to contain the resultant vibrations to a level at which the aircraft can survive at least for a limited period of time. The results had shown that the loss of 0.1 kg of mass per meter of blade length could be compensated so that the residual vibrations would stay within the current RT&B limits. Likewise, the effect of losing 9 kg of weight at the blade tip could be counteracted to the point where the remaining vibrations would just reach the temporary limits applicable to the first RT&B flight today.

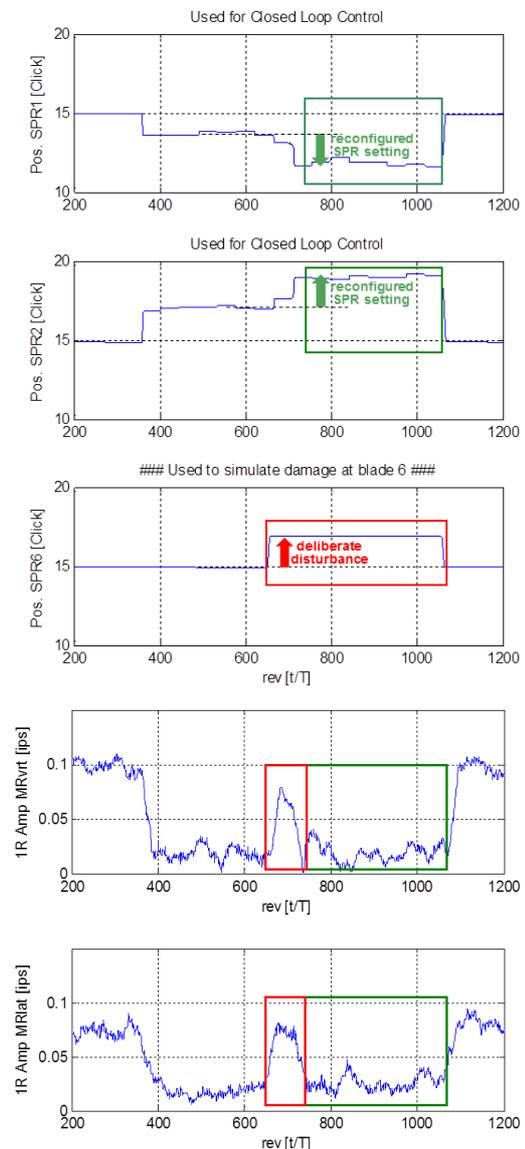


Figure 20: Simulation of automatic reconfiguration after sudden change of blade properties, simulated by a step input at one non-controlled SPR™ (top: SPR™ positions, bottom: vibrations, LF @ 110 kts)

The IFT system inherently reconfigures the SPR™ settings upon changes of the vibratory condition due to the closed loop concept of operation. Through the continuous identification any loss of feedthrough is recognized and the settings are redistributed across the blades to compensate any sudden unbalance. The reason for the locally changed sensitivity is not relevant for the success of the reconfiguration. To check this behavior, a dedicated test flight was performed. A selected SPR™, which was not assigned to the closed loop control in this case, was used to provoke a noticeable disturbance through a predefined pitch step input, thereby simulating a sudden blade change.

Figure 20 shows the time histories for this experiment. After approximately 300 rotor revolutions of closed loop controlled flight, a step input is introduced at the SPR™ of blade 6 (red box). Immediately the vibratory condition deteriorates to a level which happens to be close to that of the non-IFT-controlled reference phase. Within some 80 rotor revolutions the controller then manages to adapt the IFT inputs at the two controlled SPR™s and pushes back the vibrations to the same low level as before the onset of the disturbance (green box).

In principle, a blade exchange raises a very similar problem, however less challenging, for the traditional RT&B equipment is at hand on the ground to perform the prescribed procedures. Nevertheless, time and especially flight hours are valuable and any reduction of the required effort saves maintenance cost. Therefore, it was proposed to perform a respective experiment. The flight test center has ordered a spare rotor blade from the central depot and shipped to the flight test site. Then one of the blades was removed and the spare blade installed. The length (in default position) of the corresponding SPR™ was manually pre-adjusted according to the pre-track number that came with the spare blade. All remaining blades were left untouched, they were neither rearranged nor were the lengths of their SPR™s mechanically altered.

Figure 21 summarizes the results from this experiment. To generate respective reference measurements the IFT system was kept switched off in the initial phase of the flight. It was immediately recognized that the blade change had considerably deteriorated the vibratory condition and the standard limits (either vert. or lat.) were exceeded in all flight conditions. So equal to the bent tab experiment, the aircraft would not have been released for regular operation in this configuration. Instead the traditional RT&B procedure would have been started involving the installation of RT&B equipment, several measurement flights and mechanical adjustments on the ground. In our case, however, IFT was activated

in the air and the actuators were commanded to new positions as calculated separately for each flight condition by the IFT algorithm. And again, for most flight conditions the new vibration levels were even significant smaller than before the blade change.

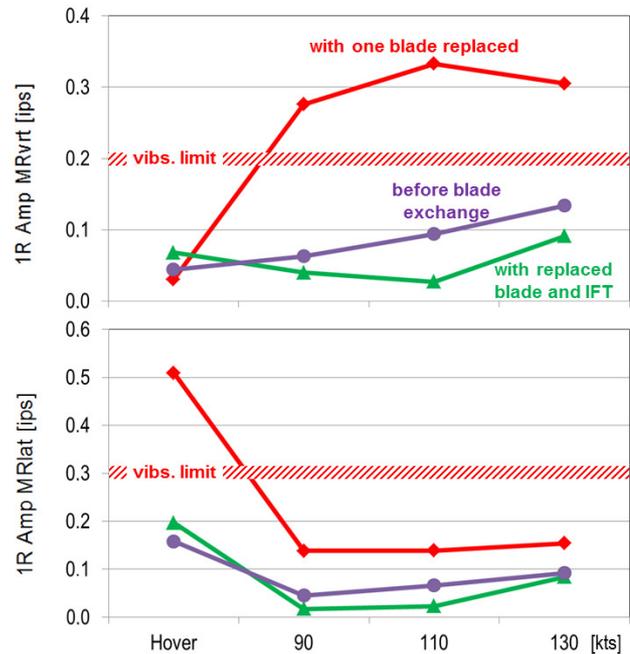


Figure 21: Compensation of 1/rev vibrations caused by a replaced blade

4.2.5. Redistribution of Computed Pitch Setting Commands across all Blades

During the initial flights, only two selected (non-opposite) SPR™s had actively been controlled. This is indeed sufficient from a theoretical point of view. Nevertheless, there are good reasons to fit more SPR™s to an aircraft, as this provides a desirable degree of redundancy and allows restricting the individual authorities while maintaining the required combined effectiveness. Smaller SPR™ authorities help to keep the vibrations within acceptable limits in the unlikely case of erratic position commands. Therefore, as mentioned above an apportionment algorithm has been implemented which is able to redistribute the computed corrections across all six blades. Different criteria can be used to optimize this distribution based on aspects like minimum local pitch change or minimum over-all track split.

In addition, a clean-up function is included to prevent that counteracting inputs (e.g. the same delta at two opposite blades) are applied which would not affect the 1/rev condition but could create higher harmonic components instead.

In [1] corresponding flight test measurements are compared. It could be shown that the residual vibration levels were very close for the cases with six vs. two blades controlled, whereas the maximum required input was typically reduced by more than 50% when using all blades.

4.2.6. System Performance during Maneuvers

All flights described so far were conducted in steady flight conditions. Due to the time it takes to collect the vibration data and extract a consistent and reliable the 1/rev component, it was not intended that the IFT controller should dynamically follow agile maneuvers. However it was of interest, whether the control needed to be paused during transient flight segments or it was possible to keep the algorithm running without experiencing any negative effects.

After the pilots had gained solid confidence in the system operation they themselves requested to expand the scope of the flight tests and proposed to fly the testbed aircraft through the whole bandwidth of operational relevant maneuvers with the IFT system kept active all the time. Results of two corresponding flights are shown in Figure 22. To be able to prove the positive impact of the system operation it was decided to suspend the closed loop IFT control approximately every five minutes for a short period of time. The particular flight conditions including several quite aggressive maneuvers are indicated above the color-coded time histories for each of the approximately 100 min lasting flights.

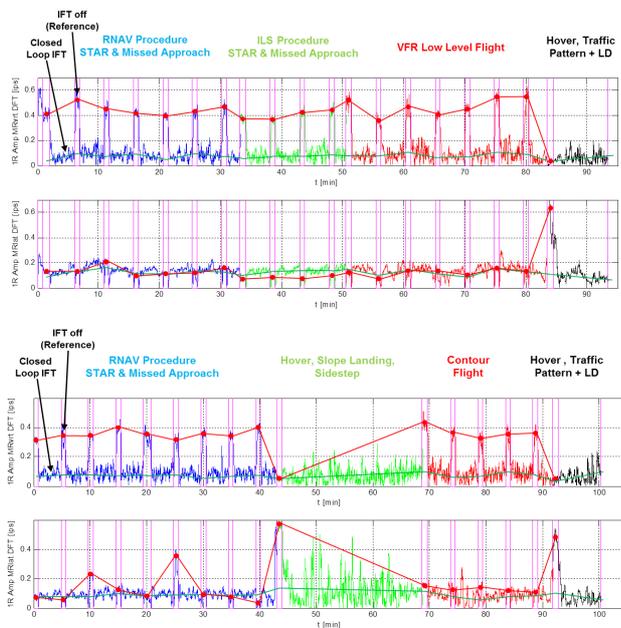


Figure 22: Closed loop controller performance during various maneuvers, after blade exchange without any RT&B (reference measurements with IFT off taken approx. every 5 min)

Throughout the flights the vibrations were consistently and noticeably smaller during the closed loop controlled sections than during the adjacent reference measurements. It is interesting to notice that in some maneuvers the two sensor locations seem to react complementary to each other. While in most cases the stronger benefit was observed for the vertical axis, in low speed maneuvers the lateral sensor showed the stronger reductions. It should also be mentioned that both flights were conducted right away with the replaced blade without having conducted any corrective RT&B activity before. This underlines the great potential to save RT&B flight hours again.

5. CONCLUSION

ZFL has designed, manufactured, qualified, installed, and certified a novel IFT system for the CH-53G cargo rotorcraft of the German Air Force. A flight test campaign has successfully been conducted to demonstrate the capabilities and benefits of the system. Throughout the program the system operation was flawless and the design has proven to be reliable and robust. Neither was a single uncommanded SPR™ motion observed nor was one of the hard stops ever touched.

5.1. Summary of Results

Based on the complete set of data collected during this flight test campaign the following key conclusions can be drawn.

Sensitivities

The identified sensitivities are widely linear and blade independent but do vary significantly with the flight condition.

Vibration Measurements

The extraction of consistent and stable 1/rev components from the partly noisy sensor signals requires sophisticated filtering and averaging (especially in hover).

Vibration Reduction

The vibration reductions achieved during the test flights were in the order of 75%, obviously depending on the quality of the initial RT&B condition.

Required Adjustments

The corrective settings that need to be applied to minimize the 1/rev vibrations vary with the flight condition. But also from flight to flight the required settings change noticeably.

Other Harmonics	Whereas in principle, certain pitch input patterns could create or amplify other harmonics than 1/rev, in none of the test flights such effects have been observed.		and larger blade dissimilarities are tolerable. This yields considerable savings through spared check flight and maintenance man hours.
Track Split	Although flat track is not enforced and to some extent track split is actually used as the physical mechanism to counteract mass dissimilarities, the tip path data recorded by the camera have never shown any critical excursions beyond the established limits.	Compensation of Creeping Deterioration	The IFT system is able to compensate slowly increasing 1/rev vibrations resulting from external factors such as water ingress, erosion or the like arising during aircraft operation or even when just parked.
Misplaced Tabs	The effect of deliberately deflected tabs could be more than just compensated by suitable flight condition dependent SPR™ inputs. As soon as the pitch settings can be re-adjusted during the flight, tab bending for RT&B purposes can be skipped in most cases.	No Compromise Settings	Through the in-flight re-adjustments much lower over-all vibration levels can be maintained compared to today's situation with fixed "compromise" settings. This reduces the vibratory loads which are detrimental to the airframe and the installed equipment
Reconfiguration	The inherent reconfiguration capability was demonstrated in a flight, during which a sudden blade change was simulated by a step input at one of the SPR™s. The controller was able to quickly recover and completely suppress the excited vibrations.	No Carry-on Equipment	No RT&B equipment needs to be installed before and removed after the repetitive check flights. The respective measurements are taken continuously and any unexpected and potentially dangerous change can be detected and compensated instantaneously.
Apportionment	The feasibility of the integrated apportionment and clean-up algorithm was successfully demonstrated. In the evaluated cases the magnitude of the maximum required input could be reduced by 50%.	Automatic Reconfiguration	The inherent reconfiguration capability improves safety and survivability and can even prevent situations in which an aircraft would otherwise have to be left behind due to excessive vibrations.
Algorithm in Maneuvers	When kept active during maneuvers, the control algorithm did not cause any increased vibrations but was able to maintain a large reduction against the reference case.		

5.2. Operational Benefits and Cost Savings

The flight test results underline the feasibility of the IFT concept and reveal its potential advantages for the operator. The benefits are related to both the safe and efficient operation of the aircraft as well as the operating and maintenance cost.

RT&B Check Flights	The number of check flights with manual adjustments can be reduced to a single "Return-to-Service" flight. The exchange of blades is less time consuming
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5.3. Productionisation and Outlook

During the design of the IFT components the application to various rotorcraft as a retrofit system was always kept in mind. Therefore, the layout of all functional components, their manufacture as well as their qualification were carried out under the assumption that they could be reused in a production system.

Under a governmental contract awarded by the German MoD, ZFL is well under way pursuing the productionisation and certification of this IFT system for the CH-53G. Although the concept and all the core components have proven their applicability, few changes derived from lessons learned during the flight test campaign will be included in the final embodiment. The current approach and the goal to

transfer the benefits to other platforms are bolstered by the following features.

- The hard- and software of the IFT system is easily scalable. Since the CH-53G version of the SPR™ had to be very short, adaptation to other rotorcraft is comparably straightforward.
- The design for a modified SPR™ to be flight tested on a UH-60 helicopter has already been completed.
- The core components as SPR™ with embedded Actuator Control Unit, slipping, and IFT Commander have already been developed according to the common standards and certification requirements.
- Endurance bench tests of the SPR™ beyond the number of cycles required for the flight test clearance have confirmed the (initial) lifetime target of 5000 FH.
- The functional and proven IFT algorithm only needs to be wrapped in a user-friendly GUI and ported from the experimental dSPACE computer to the production version of the IFT Commander.
- For the single Return-to-Service flight that will replace the whole RT&B procedure, the carry-on IFT HandHeld Unit will be outfitted with an intuitive user interface that guides the respective mechanic through the flight and the final SPR™ rigging.
- The handling will be further simplified, since in the production version even the one-time SPR™ pre-adjustment on the ground will be electrically driven and remotely controlled from the HandHeld Unit.

6. ACKNOWLEDGMENTS

The flight test program has been carried out under the contract "Development, Fabrication, Qualification and Flight Testing of an IFT System" awarded by the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw). The authors gratefully acknowledge the significant support of the flight crews, ground support personnel and the certifying staff of the Bundeswehr Technical and Airworthiness Center for Aircraft (WTD 61) in Manching during preparation and execution of the IFT flight trials.

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