



NLR-TP-99505

## **Tail shake vibration**

Objective comparison of aerodynamic configurations in a subjective environment

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## Abstract

Extensive computational fluid dynamic analysis and wind tunnel testing form part of the design of any new helicopter. Nevertheless, the so-called “*tail shake*” phenomenon is often encountered during early flight testing. A method is presented to characterise this wake related phenomenon in a tractable fashion. It is substantiated how a crew-correlated tail shake indicator was extracted from a subjective environment and developed into an objective characterisation. Amongst other rotorcraft, it was applied to the NH90 helicopter, used in this paper to demonstrate the method. The differences between two early aerodynamic configurations tested are quantified and wake behaviour highlighted, using the so-called “ $\gamma$ - $\alpha$  plot”. It is concluded that the proposed method allows objective comparison and gives insight into wake behaviour, supporting engineering decisions during development flight testing.



## **Contents**

<b>1</b>	<b>Introduction</b>	<b>5</b>
<b>2</b>	<b>What Is Tail Shake?</b>	<b>6</b>
<b>3</b>	<b>Criteria For A Characterisation</b>	<b>9</b>
<b>4</b>	<b>Characterisation Method</b>	<b>10</b>
<b>5</b>	<b>Application: Comparing Different Configurations</b>	<b>18</b>
<b>6</b>	<b>Conclusions</b>	<b>23</b>
<b>7</b>	<b>References</b>	<b>24</b>
<b>8</b>	<b>Appendix: Typical Tail Shake "Identity Card"</b>	<b>25</b>

## 1 Introduction

Interactional aerodynamics (I/A) remains, despite a considerable effort by different companies over the last two decades [1,2], difficult to predict with confidence before the first flight of a new helicopter. Examples are the EH101, Comanche and the NH90 helicopters, where at least one I/A related problem was discovered and solved for each one of these rotorcraft during flight testing. The EH101 suffered from tail shake, while excessive nose-up attitudes in transition resulted in resizing and relocation of the horizontal stabiliser [3, 4]. Reportedly, the Comanche suffered [5] a local, wake induced vibration problem in the T-tail. The NH90, although succeeding the first time with an optimal horizontal stabiliser design [6], encountered tail shake during early development flight testing.

That these problems still crop up in the flight test stage is certainly not due to a lack of effort by design teams. Extensive wind tunnel test campaigns before and after first flights are partially dedicated to I/A subjects [2, 3, 6, 7, 8, & 9]. General complexity of modern, compact helicopter designs, associated with scaling difficulties, are contributing factors towards limited success in predicting I/A related vibration problems. Reproducing the complex, mostly turbulent flow aft of the main rotor on a scaled model requires a considerable investment. Even when the flow is perfectly modelled, predicting *with confidence* how the structure will respond to the flow is probably impossible. Therefore, the risk remains that I/A related vibration problems will be encountered during flight testing of a new design.

## 2 What Is Tail Shake?

Tail shake is a phenomenon which, depending on the severity, may adversely affect crew efficiency, figure 1. It is a recurring phenomenon on single main rotor helicopter designs, and has been clearly identified to be an interaction of a turbulent wake with the tail part of the structure, as is evident from most of the references cited. See figure 2. The composition of this wake is a function of different factors, not the least of which are the aerodynamic design of main rotor hub, engine intakes and exhausts, cowling shapes and the proximity of the rotor to fuselage.

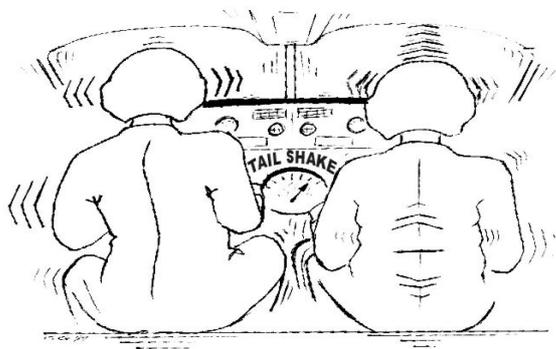


Figure 1: Tail shake in the cockpit

Given the “right” combination of factors, the wake/tail interaction results in the excitation of the lower elastic modes of the structure, usually in a lateral sense and in the vicinity of 1 to 2/rev. Therefore the tail shake response is shaped on the first lateral bending mode which is a two node mode. This means in practice that the vibration is mostly felt in front of the forward node, i.e. on flight crew stations, figure 3.

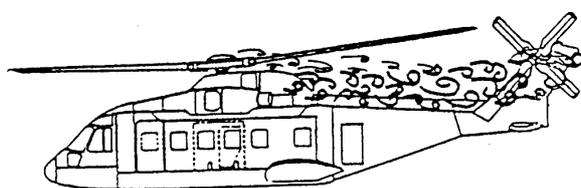


Figure 2: Wake/tail aerodynamic interaction

Another typical aspect of tail shake is that it has an unsteady random character, indicating that the wake induced excitation is also unsteady of nature. The crew feels lateral “kicks”, sometimes characterised by the crew as a low-frequency vibration, also called buffeting.

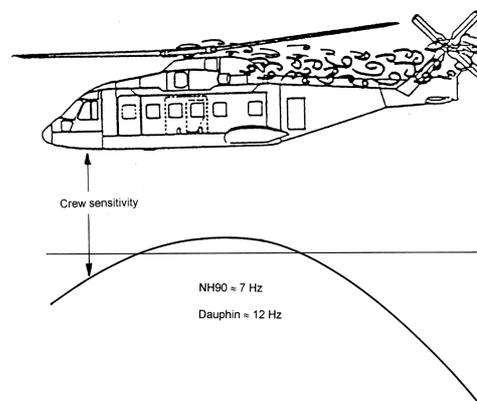


Figure 3: First lateral bending mode (2 nodes)

### Why subjective?

There are two important reasons why tail shake, or any vibration problem for that matter, may be a subjective topic of discussion. The first is related to the crew in a complex dynamic environment, and the second to the data reduction.

⇒ During development flight testing of a new rotorcraft, the crew is often subjected to a dynamic environment rich with harmonic and non-harmonic vibrations. The pressure of freezing the definition of various sub-systems, including aerodynamics, as soon as possible, calls typically for different flight profiles and different dynamic and aerodynamic configurations. Unfortunately, due to practical considerations and constraints, the order in which test flights are executed is often not ideal from an investigative point of view. For example, performance, handling qualities and vibration flights may be mixed up, depending on weather conditions, availability of to be tested equipment, etc.

This complex and demanding environment sometimes obscures the causality of certain phenomena, such as vibration. It will be demonstrated that an unexpected secondary result, caused by a different flight profile, caused everybody (crew and data analysts) to revise their judgement on a given configuration. It will also be demonstrated why this happened.

The crew find themselves in a subjective environment also because the relative importance of a specific vibration frequency may change with time. Each crew member is subjected to a three dimensional superposition of different harmonic and non-harmonic frequencies. When one of these frequencies are reduced, e.g. when N/rev vibration absorber tuning is optimised, the overall perception of the vibration environment may change.

⇒ Data reduction also tends to be subjective. The first trap is to assume that vibration is measured in absolute terms. As vibration is essentially measured at discrete points on the structure, the relationship between crew feeling and vibration measurement results is often ambiguous, and sometimes contradictory. Therefore, *relative differences* extracted from the measurements should correlate with crew feeling.

Another source of subjectivity obviously lies in the processing and analysis: Fundamental to this problem is, again, the rich vibration environment. *What is really the important information contained in the measurements? How to extract this information from the measured data?*

### **How to be objective?**

Again referring to figure 1, the goal is to find an objective means of measuring the tail shake vibration, but also to present the data in an objective format. Objectivity in processing and presenting vibration data is a dynamic process. This process is strongly driven by crew opinion, especially in the early stages of identifying the dynamic behaviour of a new rotorcraft. A fundamental necessity in this process is to find an indicator, or set of indicators, which is well correlated with crew opinion. Once this goal is achieved, objective support of crew opinion becomes possible.

In the case of tail shake, identifying the frequency content and nature of the vibration was an important step towards finding the representative indicator, as will be demonstrated later on.

Finding a way to understand the influence of the flight profile on tail shake was another target, i.e. to clarify the relationship between the phenomenon and flight parameters related to the aerodynamic origin.

Finally, another way to insure objectivity over an extended period of time, is to have as much as possible hands-off processing. This calls for a systematic, methodical approach.

### **3 Criteria For A Characterisation**

Before going into the details of the method developed, the criteria for a characterisation of tail shake is listed in order to “measure” the eventual “success”. Some of them have already been covered, but are nevertheless listed:

The objective of the method presented here is to characterise tail shake in terms of a limited number of parameters, meeting the following criteria. It should:

1. correlate with crew opinion,
2. support objectively the comparison of different configurations tested (quantify the differences),
3. identify critical flight cases,
4. be easily adaptable to different rotorcraft,
5. limit the amount of processing and data-storage required, and
6. give some clues as to the wake behaviour (path, strength, etc.).

#### 4 Characterisation Method

The interactional nature of tail shake was the driver in developing this method, the phenomenon being an interaction between *aerodynamic excitation* and *structural response*.

Intuitively, the excitation, being aerodynamic, should be related to flight parameters describing the relative airflow. These include potentially indicated airspeed (IAS), fuselage incidence and sideslip, as well as vertical speed.

As for the response, the nature of the tail shake mode should be taken into account. Any measurements correlated with crew feeling may be used. Given the two-node nature (figure 3), a logical location of such a measurement is on the extremities of the structure. Naturally the area between and close to the nodes should be avoided. For the example presented later, the lateral acceleration on the floor beneath the pilot's seat proved to be a good measurement.

The notion to characterise the response in terms of the excitation is further developed in figure 4, showing the framework of the approach. In the following sections the processing applied to extract two indicators representative of respectively *excitation* and *response* is described.

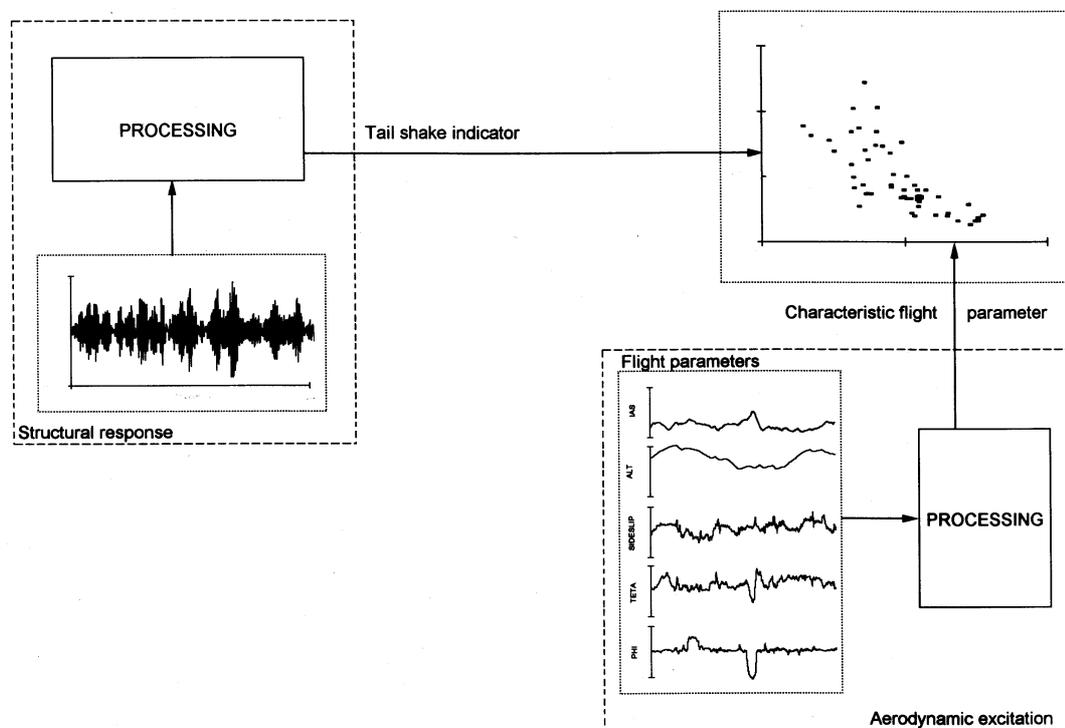


Figure 4: Processing philosophy

The characterisation method is described using flight test data from the NH90. **As the power of the method is best illustrated when differences between configurations are significant, the examples used are taken from results in the early stages.** Therefore these results do not reflect the current status of the NH90, nor is it the intention to discuss the merits of different aerodynamic solutions.

### Tail shake response indicator

The argumentation used to derive this indicator is demonstrated using the NH90 as an example. Later it will be shown that this indicator is easily adaptable to other rotorcraft.

The nature of the measured response  $\gamma_y$  is defined by the spectral analysis and the raw time history (excluding 4P and higher frequencies) shown in figure 5. The spectrum shows clearly a region of frequency amplification between 1P and 2P, while the time history reveals the “waving” or unsteady character.

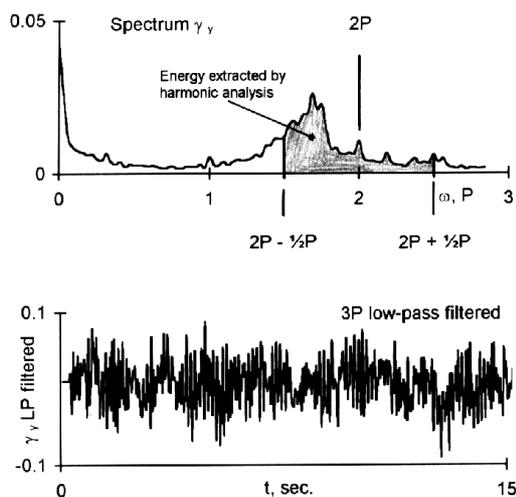


Figure 5: Nature of tail shake response

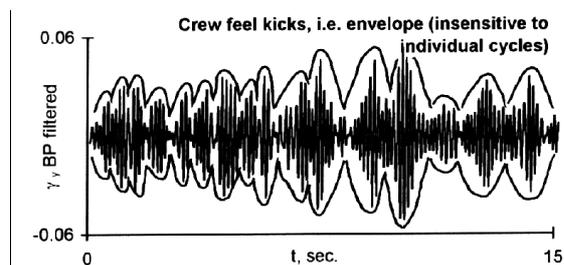


Figure 6: Response and crew feeling

Much time was therefore spent in telemetry sessions in the search for a tail shake indicator. From the real-time, band-pass filtered  $\gamma_y$  signal it was clear that what the pilot experienced as lateral, low frequency, random vibration, was in fact the tail shake

mode responding to intermittent excitations. Another important observation was that the pilot’s sensation pertaining to the strength of the tail shake was proportional to the peak values of the filtered response. Figure 6 shows the relationship between the waving response and the crew feeling.

Simply stated, the essential information to be maintained during data extraction are the peak values felt by the crew, as well as the frequency content. The challenge was the following:

- find a simple processing which could be used on an ongoing basis (long flight segments)
- avoid using time histories because it consumes a lot of disk space (only the envelope of the  $\gamma_y$  signal is useful)

The answer to the first challenge was to use a classical helicopter vibration analysis tool: harmonic analysis.

The principle of conservation of energy dictates that the time-domain energy of a signal should also be reflected by the frequency domain representation of the same signal. Simpler stated: the Fourier representation should approach the original signal. The consequence of this principle is that the second harmonic represents all the energy in the frequency band  $[2P - \frac{1}{2}P; 2P + \frac{1}{2}P]$ . Looking again at the spectrum in figure 5, this seems to be a good approximation. Harmonic analysis is a powerful *energy extractor*, as shown in figure 7.

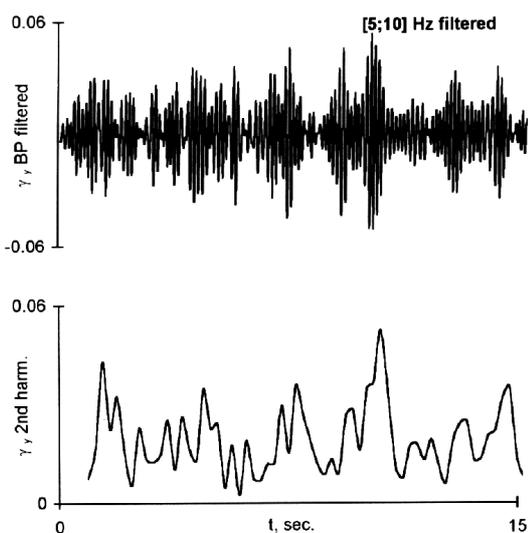


Figure 7: Energy extraction with harmonic analysis

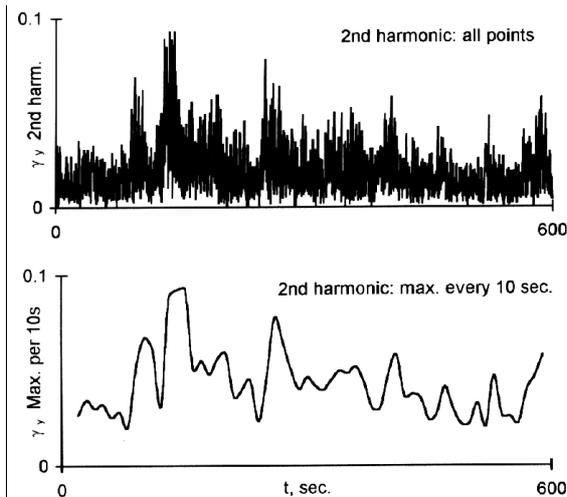


Figure 8: Second reduction step (10 min. segment)

Taking the second harmonic of  $\gamma_y$  instead of working with time histories already significantly reduces the number of points to be stored (typically in the order of a factor of 64 for the NH90). Also this first reduction step maintains frequency content as well as the waving character. But, figure 8 (top half) in fact shows that the reduced signal still contains *too much* information if used for a longer period.

Therefore a second step is introduced, being a simple statistical operation. The maximum value of the second harmonic of  $\gamma_y$  per time window is retained. For the NH90 this time window was tuned to 10 seconds, a compromise between representativity and data volume. Figure 8 (bottom half) shows the remaining signal which is still representative of the original signal envelope. The second reduction step reduces the amount of data by another factor 40 for the NH90, resulting in a total reduction factor of the order of 2500.

The applicability of this method to any rotorcraft stems from the fact that the harmonic analysis can be manipulated to some extent. The following procedure has been successfully applied to rotorcraft with different modal signatures (frequency and mode shape):

1. Spectral analysis to localise tail shake energy, i.e. central tail shake frequency,
2. Selection of harmonic analysis parameters (number of rotor revolutions and selection of relevant harmonic) to have most of the tail shake energy inside harmonic bandwidth,
3. Validation as described in this section (representativity of harmonic analysis compared to filtered time-history).

Increasing the fundamental period (number of revolutions) of the Fourier analysis reduces the frequency resolution. In this way a structural mode will fall inside one of the discrete frequency bands. Naturally, care should be taken with rotor harmonics which may have significant levels compared to the tail shake mode, as this will distort the results. In our example the 2P line does not influence significantly the total amount of energy in the  $[2P - \frac{1}{2}P; 2P + \frac{1}{2}P]$  band, figure 5.

At this point, criteria 1, 4 & 5 are met:

- correlate with crew opinion,
- easily adaptable to different rotorcraft,
- limit the amount of processing and data-storage

### **Excitation indicator**

At this point the suspicion that fuselage incidence is a contributing factor towards NH90 tail shake was clearly confirmed by a presentation such as figure 9. Shown are two different flights, A and B, with identical aerodynamic configuration. However, the general crew feeling was that flight B was worse from a tail shake vibration point of view, a fact well supported by the response indicator  $\gamma_y$ . Clearly the flight profiles were also different. It should be noted that flight A was dedicated to vibration identification, while flight B was engine testing at altitude. For the latter flight, crew attention was focused on engine behaviour, with vibration impressions being secondary results (nevertheless important).

Despite the crew-correlated response indicator described earlier, it is evident from figure 9 that one still has a subjective environment. The central question being: *how to demonstrate that these two flights indeed have identical tail shake behaviour?*

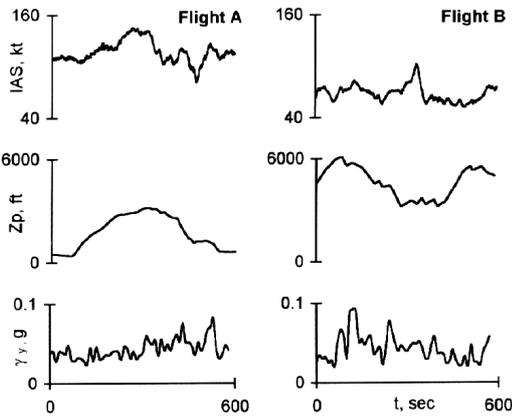


Figure 9: Different flights, identical configuration, different crew opinion (10 minute flight segments)

Looking for relationships, the tail shake indicator was set out against all the primary flight parameters. One important parameter, fuselage incidence, was however absent. Even if available as a direct flow measurement, the error induced by the rotor wake would probably have precluded it from use in this process.

The average fuselage incidence (angle between free stream velocity and fuselage X-axis), ignoring rotor wake induced effects, is a function of IAS (kt), vertical speed (ft/min) and pitch attitude:

$$\alpha_c = f(\text{IAS}, V_z, \Theta), \text{ deg} \quad (1)$$

where the subscript c denotes calculated, and:

$$V_z = dZ_p/dt, \text{ ft/min} \quad (2)$$

where  $Z_p$  = pressure altitude, ft.

Equation 1 then becomes:

$$\alpha_c = -\Theta + \sin^{-1} \left( (0.3048 V_z) / (60 \times 0.51 \text{ IAS}) \right), \text{ deg} \quad (3)$$

Studying a phenomenon where aerodynamics play clearly a dominating role, all available parameters describing the airflow relative to the fuselage are of potential importance. In this

case they are: IAS, sideslip  $\beta$ , incidence  $\alpha_c$ , vertical speed  $V_z$ . Of these, it will be shown that  $\alpha_c$  is the most characteristic.

[Note: The true  $\alpha_c$  (with respect to free stream velocity) should in fact be based on true airspeed. However, for comparative purposes, IAS is sufficient.]

The evolution with time of the *excitation parameter*  $\alpha_c$  (calculated incidence) is shown in figure 10 together with the *response parameter*  $\gamma$ . **There exists a clear and similar relationship between tail shake and incidence for the two flights, i.e.  $\gamma$  increases with  $-\alpha_c$**

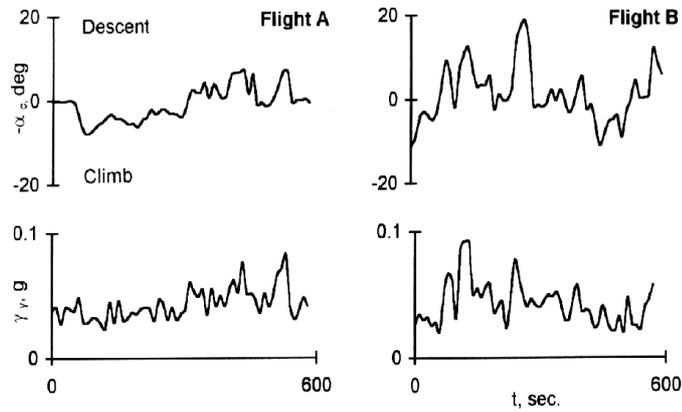


Figure 10: Tail shake and flow parameters

### Characteristic tail shake plot

The two representative indicators developed thus far result in the so-called  $\gamma$ - $\alpha$  plot for tail shake, figure 11. The data shown in the plot comes typically from a flight where, at constant IAS, the vertical speed was varied. In this way, a range of  $\alpha_c$  of at least  $[-20;20]$  deg. is covered, corresponding to  $[-3000; 3000]$  ft/min vertical speed at, say 80 kt. On the NH90, as on other helicopters, descent at around 80 KIAS was one of the critical flight cases.

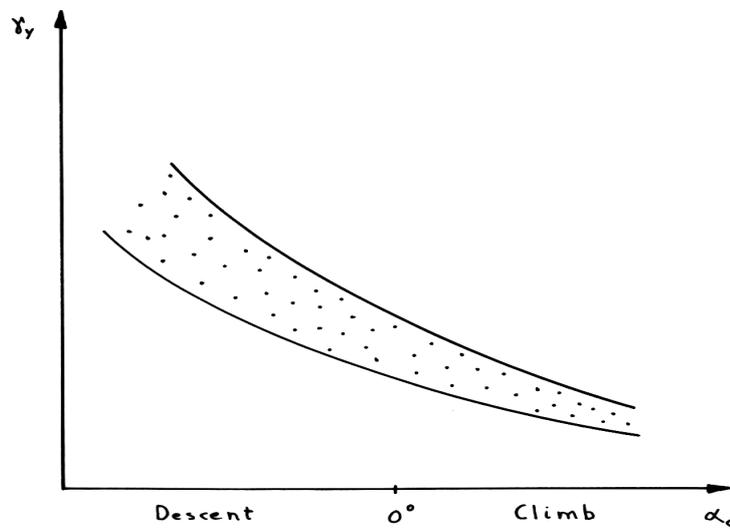


Figure 11:  $\gamma$ - $\alpha$  plot for tail shake

Note: The scatter seen confirms that of a similar plot presented in ref. 10. Also refer to the plot in the annex.

The  $\gamma$ - $\alpha$  plot is *characteristic for the quasi-static tail shake behaviour of the rotorcraft*, in particular during the early stages of flight testing. The characterisation presented here allows a systematic tail shake identification to be executed after an aerodynamic modification which may affect tail shake. The method consists of performing  $V_z$  sweeps at different air speeds. The result of such a set of sweeps is shown in the annex, containing all the relevant parameters previously mentioned (IAS, sideslip  $\beta$ , incidence  $\alpha_c$ , vertical speed  $V_z$  and  $\gamma_y$ ). This presentation serves as the tail shake identity card, and is in the first instance used to verify that the test was executed under the same conditions as before.

Three distinct ranges of incidence is identifiable from the  $\gamma$ - $\alpha$  plot. Negative incidence is associated with descent, positive incidence with climb, and a window around 0 deg. with level flight, depending on speed and longitudinal centre-of-gravity.



Using the proposed method, it was possible to demonstrate that the tail shake behaviour of flights A and B were indeed identical and that the different crew opinion was caused only by the difference in flight profile.

At this point, criterion 3 is also met:

- critical flight cases are identified

What remains to be demonstrated is how this method is applied to meet criteria 2 and 6:

- support comparison of different configurations
- give some clues as to the wake

## 5 Application: Comparing Different Configurations

In this section, the  $\gamma$ - $\alpha$  plot is applied to two different aerodynamic configurations of the NH90. It is demonstrated how this method enables a clear distinction between these two configurations.

### Configurations compared

The first flight configuration of the NH90 was with engine air intakes with low dynamic recovery, colloquially called “static” intakes. Later, a first generation “dynamic” intake design was tested. See figure 12. Changing from static to dynamic intake configuration, a severe tail shake was observed by the crew, even in level flight.

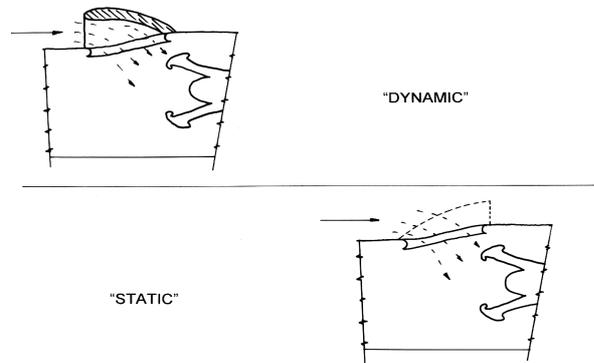


Figure 12: Static and dynamic engine intakes

These two configurations are compared to demonstrate the features of the  $\gamma$ - $\alpha$  plot.

### Quantifying the differences

Figure 13 puts the  $\gamma$ - $\alpha$  plot of the “static” and “dynamic” configurations side-by-side. It is immediately clear that the tail shake behaviour in terms of average fuselage incidence is significantly modified by the dynamic intakes. The notion of a relative shift in incidence led to the definitions shown in figure 14.

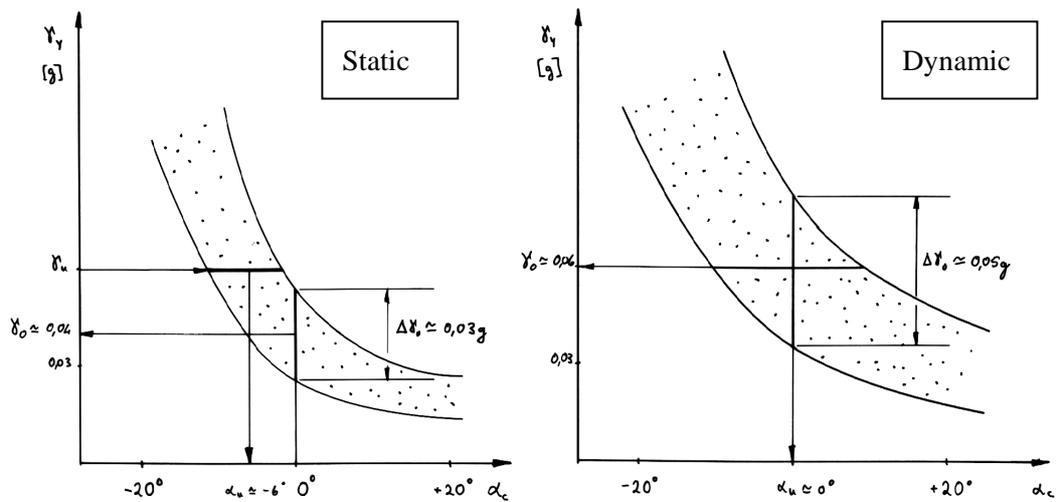


Figure 13:  $\gamma$ - $\alpha$  plot: Static vs. Dynamic intakes

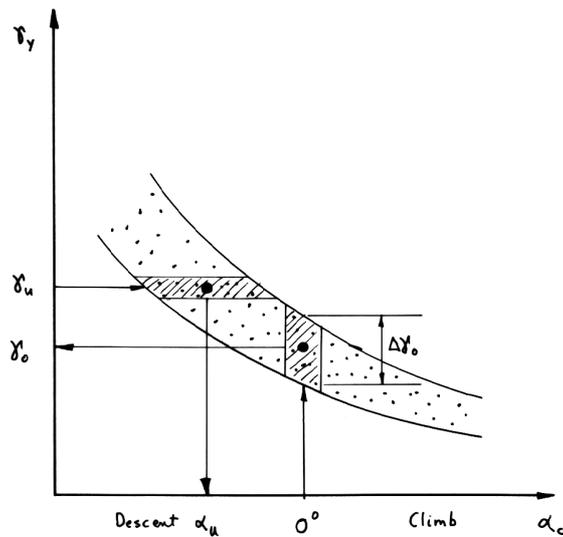


Figure 14: Features of the  $\gamma$ - $\alpha$  plot

Note that averages are taken in windows around the values of interest to accommodate statistical variations between flights (scatter referred to earlier).

The characteristic parameters from the  $\gamma$ - $\alpha$  plot are:

- $\gamma_{y_o}$  : represents the average tail shake level in level flight
- $\Delta\gamma_o$  : represents the scatter in level flight. This is an important parameter, as the pilot feels individual "kicks", and not the average
- $\alpha_u$  : average incidence associated with unacceptable average tail shake level (0.06g for the NH90)

These parameters uniquely identify the tail shake behaviour of a given aerodynamic configuration of the NH90. They may now be used to quantify the differences between different configurations. Table 1 presents a summary of these parameters, showing the effect of dynamic intakes.

**Table 1: Tail Shake: Static vs. Dynamic Intakes**

Parameter	Static	Dynamic	$\Delta$
$\gamma_{y_o}$	0.04	0.06	+50%
$\Delta\gamma_o$	0.03	0.05	+60%
$\alpha_u$	-6°	0°	+6°

### Clues for wake behaviour

The  $\gamma$ - $\alpha$  plot serves primarily as a means of identification and objective differentiation between configurations, as was shown in figure 13 and table 1. However, the clear relationship with incidence could also serve as a basis for gaining insight into wake behaviour.

Aerodynamic modifications may modify the wake behaviour in different ways. Figure 15 presents hypothetical  $\gamma$ - $\alpha$  plots, from which some intuitive inferences could be drawn in terms of wake behaviour.

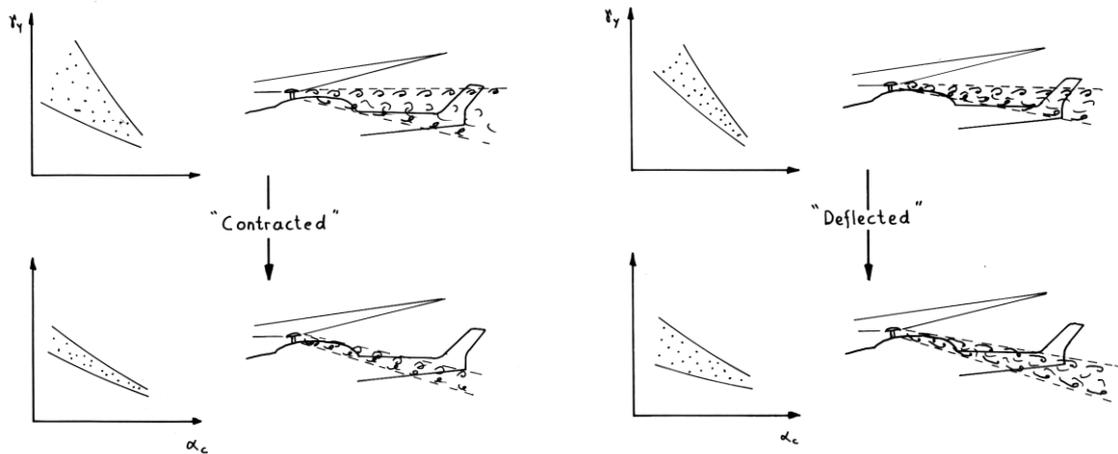


Figure 15: Insights into wake behaviour

On the left, the wake is effectively *contracted* by the aerodynamic modification. In other words, the wake volume in the tail area is reduced. This is reflected mainly by the  $\Delta\gamma_0$  parameter. A more direct interpretation, directly from the  $\gamma$ - $\alpha$  plot, is that for the same tail shake level  $\gamma_y$ , a wider range of  $\alpha_c$  are found where the wake is less contracted.

On the right hand side of figure 15, the wake is *deflected* by some means. Two effects are generally simultaneously present:

- pure wake deflection (i.e. implicit  $\alpha$  shift) relative to sensitive impact area
- change of impact area and associated sensitivity (i.e. implicit  $\gamma$  shift, especially for a 2 node mode)

An implicit prerequisite for comparison is that the mode remains constant; i.e. structural modifications may influence directly the response parameter  $\gamma_y$ .

Obviously the wake behaviour is never as simple as supposed by these hypothetical examples. Nevertheless, similar effects were indeed observed, amongst others on the NH90. A classical remedy for tail shake, the hub fairing or beanie, clearly showed a wake deflection in the downward sense, consistent with the intended function of this device. However, other effects, such as wake *contraction* and/or different wake energy levels may complicate the interpretation of the  $\gamma$ - $\alpha$  plot.

In this sense, knowledge about the flow separation areas gained by other means, such as in-flight flow visualisation and/or pressure distribution measurements [11], or wind tunnel tests [9], may complement the knowledge from the  $\gamma$ - $\alpha$  plot.



Now also criteria 2 and 6 are satisfied:

- support comparison of different configurations
- give some clues as to the wake

Nevertheless, the limits of this method were obviously approached when converging towards an optimum solution for tail shake. It becomes increasingly difficult, both for the crew and the data analysts, to distinguish between configurations.

## 6 Conclusions

A method was developed allowing a clear identification of tail shake behaviour. The method characterises the tail shake by means of accelerometer data, together with standard flight parameters. It is concluded that:

1. Departing from an indicator correlated with crew opinion, a characterisation method is proposed. It is **tractable** (semi-automatic processing; significant reduction in data volume), identifies **critical flight cases**, and is easily **adaptable** to other rotorcraft.
2. The method allows **identification and comparison** of different aerodynamic configurations
3. Insight into **relative wake behaviour** was gained. For the NH90, it was possible to clearly quantify wake *deflection* due to different aerodynamic devices tested.
4. The method proved a powerful evaluation tool in support of engineering decisions during development flight testing.

## Acknowledgements

The authors would like to acknowledge the contribution of the overall NH90 flight test team.



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Annex: Typical Tail Shake "Identity Card"

