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STALL-FLUTTER SECOND-FLAP INTERACTION ON A ONE BLADED BEARINGLESS MODEL ROTOR

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ABSTRACT

Wind generator experiments on a 1.212 m. diameter one-bladed bearingless wind turbine model rotor were performed for the principal purpose of defining experimental conditions for parameter identification of ONERA dynamic stall, lift model coefficients,
from a model of the present size or a contingent lager. Incidental to these tests a severe interaction between the second flap and stall-flutter was encountered; this phenomenon constitutes the subject matter of this paper. Particular is that the second flap frequency is approximately half the torsion one. This behaviour is similar to an incident on a full scale prototype wind turbine rotor showing this sort of interaction, the second (elastic) flap and torsion frequencies being nearly equal. In both cases unsteady drag seemes to participate in this phenomenon.

INTRODUCTION

In the thirties stall-flutter was clearly identified by Studer and Rauscher, refs. 1 and 2. Their findings were quickly confirmed by others (refs. 3 and 4) and rather extensively studied in Britain around the second world war (e.g. refs. 5-8). There-after NACA initiated the rotating case (e.g. ref.9) noting that propellors and wind tunnel fans have been known to fail; in many cases probably caused by stall-flutter. By contrast an autogiro descended unaffected with a substantial part of the rotor disk showing dynamic stall, ref.10.
Beside the hardly manageable explosive development of stall-flutter research due to helicopters (e.g. refs.11 and 12) in the seventies Delft University of Technology (DUT) was confronted with stall-flutter on a curved plate wind turbine rotor for developing countries with two encastré blades (refs.13 and 14).
A more recent contribution of DUT to this research was the comparison between experimentally determined (stall) flutter and the ONERA dynamic stall model by using an unusual one bladed bearingless model rotor (refs. 15, 16 and 17).

Further limited experimental activities in the eighties and in the nineties after a substantial improvement in the speed uniformity of the wind generator will be briefly reviewed to frame the observed stall-flutter second flap interaction.

Because this interaction was incidental to the purpose of the tests, and aggravated a potential fatigue problem of the model flexbeam, only limited data were acquired in 1993. However, by considering a comparable event on a full scale prototype wind turbine, which will be briefly described, it is believed that sufficient material is present to suggest the source of this phenomenon.

BRIEF DESCRIPTION OF PREVIOUS EXPERIMENTS

In the early eighties at DUT a flutter research model was designed and tested, which may be described as a rotating oblique T-tail. Main purpose of the investigation was the calculation validation of classical flutter of this unusual configuration (ref. 18). A succesful spin-off of the used one bladed bearingless design was a first check of the ONERA dynamic stall model for

a rotating case, basically proving the aptitude of this model for stall-flutter calculations (ref. 15). For these tests the tip-vane had been removed while mass/inertia effects were simulated by "Chinese weights".
At that time already the high non-uniformity of the open jet wind generator and the fact that stall-flutter occured in the (sub-)critical Reynolds number range were considered limitations of the result.

On a modest scale explorative experiments continued thereafter until 1988 introducing e.g. left and right yaw, 1/20 pie piece gauze (creating a local gust) and tilt. These conditions barely influenced binary flutter occuring at a tip Reynolds number of about 500,000, while stall-flutter behaviour at roughly half that value did not show signs of a limit-cycle phenomenon; consequently -rotor speed being the primary variable- the stall-flutter region could not be penetrated above 5.5 m/s tunnel speed.

In the final tests of that epoch the mass/inertia simulation was removed, giving less violent behaviour, although indications of limit-cycle were still not apparent. What was left were uncertainties about:

- the so-labeled "Gabel-Tarzanin" effect (blade torsional tuning with respect to stall-flutter, e.g. ref. 19),
- low-Reynolds number effects,
- the effect of trip-wires (possibly changing leading edge into trailing edge stall),
- non-uniformity of the wind tunnel velocity profile (± 5%).

This defied mid-eighty hopes to extract ONERA dynamic stall, lift model coefficients from a rotating model blade with the available equipment.

By 1992 the "Gabel-Tarzanin" effect had been questioned by other researchers (ref. 20), and the uniformity of the wind generator had been substantially improved (ref. 21). The latter was a succes: a clearly stabilized amplitude was evident up to 6 m/s tunnel speed. Also, from tuft behaviour during slow rpm (incidence) variations, two-dimensional, wind tunnel-like hysteresis effects were manifest. Moreover a thinner flexbeam was introduced inter alia to lower reduced frequency (independantly). From a torsion calibration of this element it followed that deflections up till then had not exceeded ± 1°, while torsion straingauges could stand ± 20°. This would enable stall-flutter measurements at a tip Reynolds number around 350,000 allowing ±10° of torsion excursions. Alternate 45° tape layers around the flexbeams were intended to control excessive pitch excursions to some extent.

In a 1993 test two flexible elements were to be evaluated with and without trip wires and with and without the same amount of alternate 45° tape layers in an attempt to reach the highest Reynolds number during stall-flutter.

ELEMENTS OF THE 1993 TEST SET-UP

The model is a stripped variant of the one bladed bearingless tip-vane turbine research model from the eighties (ref. 16). With the exception of a retained heavy tipweight -67% of the blade weight, because of the extreme light blade and the absence of a flap stop- the model fairly well resembles a flexbeam tail rotorblade, although the twist is autogiro-like and the maximum tip speed only 80 m/s. There are no controls or built in δ_3, also precone, droop and sweep are absent.
The model consists of a hollow four-ply limewood blade spar with alternate fiber layers at 45° with the centrifugal force. The blade can be connected to the hub by several Dural ST-T3 flexbeams of different thickness. A split bushing in the hub permits ± 6° pitch adjustment, but for the sake of limiting the number of variables the majority of the tests has been done with

zero pitch angle. Moreover this happens to result in the optimal tip-speed ratio. Flexbeam pitch was also zero. Because the constant chord blade - with a NACA 0012 section - has a linear 0.1 radian twist between the root and 99%R, there is ~ 2° pre-twist at the 75% blade span position. Further model properties are tabulated in the Appendix.
All flexbeams were instrumented with strain-gage bridges to measure flap and torsion moments. The rotor axis had a torsion bridge as well. Because the flexbeam torsion bridge by its dimensions, orientation and location (8,7% R) crosstalkes bending and lag, only this bridge was used to transfer signals to the fixed world. Until the beginning of this year only one transmitter transfered signals from the rotating system.

Fixed system instrumentation included a receiver, a 10/rev and 1/rev signal, the latter also triggered a strobe. The resulting data were fed in a Fast Fourier Transformer for on-line analysis, in the 1993 case they were recorded on analog tape as well. A video system to survey the backside of the rotor completes the main equipment.
The stand, drive and controller -remnants from earlier flutter and tipvane tests- do not call for special comment here. The windgenerator is depicted and described in ref. 21. Of importance is the substantial improvement of the open jet velocity uniformity (± 1,5%) since the end of 1991, which is considered to be adequate now.

TEST PROCEDURES

To prevent excessive coning and to avoid classical flapping torsion with attached flow {n> 19,9 Hz) the rotor is run-up without wind to a value giving the optimal tip speed ratio for the intended windspeed. If the latter is reached, the blade flow is still fully attached, checked by inner, middle and outer tuft; an attempt to limit fatigue loading.

While monitoring tuft behaviour tipspeed is reduced until the outer tuft is completely detached unless the cone angle is considered unacceptable or unless r.p.m control loss is imminent. This because the controller is confused if the rotor power output is more than about 300W, which can be posponed by one to four Prony brakes up to 10 m/s windspeed, using the massive axis as a heat sink. It should be noted that in accordance with ref. 22, the power does not diminish although an increasing part of the blade root is stalled.
While exploring the test envelop with the unmodified 1.5 mm flexbeam -in order to determine the number of nesessary Prony brakes- deviations from straight lines of tuft behaviour (attached or separated flow) through the origin in figure 2 for the middle and outer tuft appeared.

It was concluded that the violent torsion movements also influenced tuft behaviour at the 10% chord position, so they were relocated at 25% to minimize the effect. For translation purposes this meant relatively slow runs at speeds between 4 and 10 m/s.
In the meanwhile alternative 45° tape layers were applied to the flexbeam raising the torsion frequency from ~ 45° Hz to ~ 50° Hz. Descending through the r.p.m. range at 8,5 m/s windspeed an unusual second flaplike motion showed up as soon as the root commmenced stalling; also evidenced by a 25 Hz peak in the frequency spectrum by the earlier mentioned cross talk effect, reaching maximum amplitudes at 12,3 Hz. This extra fatigue loading motion disappears slowly when decending to 8.9 Hz leaving the scene exclusively to the limit cycle torsion motion with ± 7° excursions in this case. It is noticeable that the non-rotating second flap node is at 83%R.
This phenomenon being quite incidental to the test purposes and considered a supplementary fatigue threat to the model trip wires influences, if any, were discarded - that year- in favour of a video recording as seen from the tip in addition to the standard 3/4 view. All tests were video- and analog tape recorded because of allready existing fatigue worries.

A FULL-SCALE VARIANT

Stall-flutter second elastic flap interaction previously occured on a prototype 21,2m diameter horizontal axis wind turbine (ref. 23). In this two-bladed design with teetering hinge and flexbeams power output is governed by orientable 23,6% R blade tips with NACA 44 series section, with an estimated mean relative thickness of 15%. The incident happened during a starting attempt in a nearly 20m/s wind. Pitch angle excursions -as measured from video images recorded from the hub - attained values of nearly +30° and -15°. The second elastic flap had approximately the same value as the torsion frequency. Although no tufts were present during the event, dynamic stall may have occured on both sides. In fact this was noticed on a functional scale model during wind generator tests in November 1989. By contrast stall is only at one side in the comparable model case.

CONCLUSIONS

The phenomena encountered during the model tests and the full scale variant recall variable high Mach number drag variations in helocopter forward flight, which can combine the second (elastic) flap and torsion modes; So it might be concluded that:

1) The second (elastic) flap mode seems to provide unsteady drag forces during dynamic stall the opportunity to contribute to the limit cycle stall-flutter excursions, if the pertinent frequencies are about equal or if the second flap frequency is approximately half the torsion one.

2) In the model case the edge wise mode - gravity driven - may have played a role too. Moreover, a negative spring effect of the unsteady drag should be considered. This would require further investigation.

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APPENDIX: MODEL PROPERTIES

The model geometric properties are shown in Table 1. Rotor mass properties are given in Table 2. The nonrotating frequencies for blade up and blade horizontal, with and without artificial coning by a 0,1 radian tilt of the stand, do not differ significantly from the tabulated values in Table 3 with the blade down. Measurements were made by loudspeakers excitation in the appropriate directions. From these tests the position of the second flap node was obtained as well.

Table 1 Rotor geometric properties.

Radius, m	0,606
Blade root radius, m	0,180
Blade chord, m	0,1000
Blade twist between R=0,600 m and R_r, radians	0,1
Solidity	0,0526
Flexbeam length, m	0,17

Flexbeam width, m	0,01600
Flexbeam thickness, m	0,00150
Second flap node, % radius	83

Table 2 Rotor mass properties.

Blade mass, kg	0,1039
Tipweight unit mass, kg	0,0668
Blade spanwise c.g. % radius	76,1
Blade chordwise c.g. % from LE	26,1
k_θ static, Nm/rad	3,2
Lock no blade only	17,0
Lock no tipweight unit included	3,1

Table 3 Blade nonrotating frequencies

Blade mode	Model frequency (Hz)	Model frequency with tape layers (Hz)
First flap 1,5	*1,56*	
Second flap	26,	27,5
First lead-lag	12,5	
First torsion	44,7	49,2

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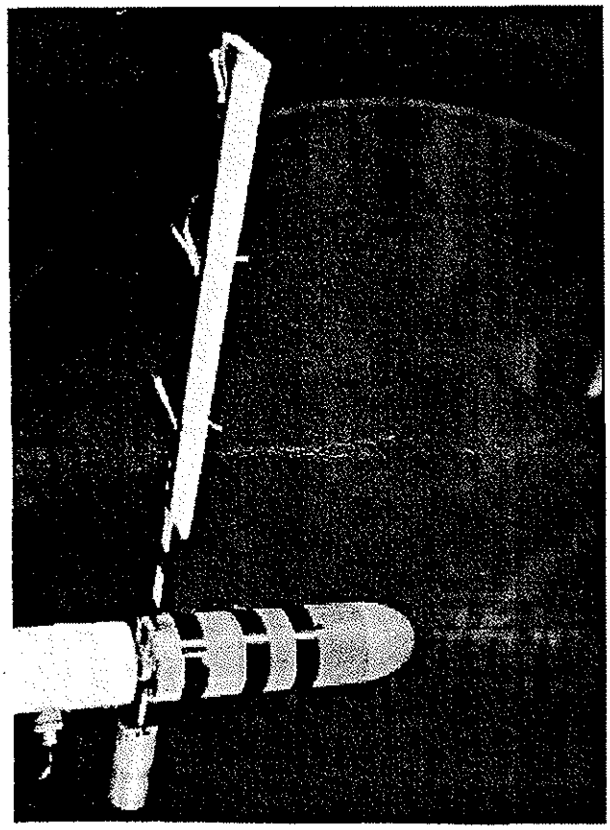

Fig. 1: The model rotor

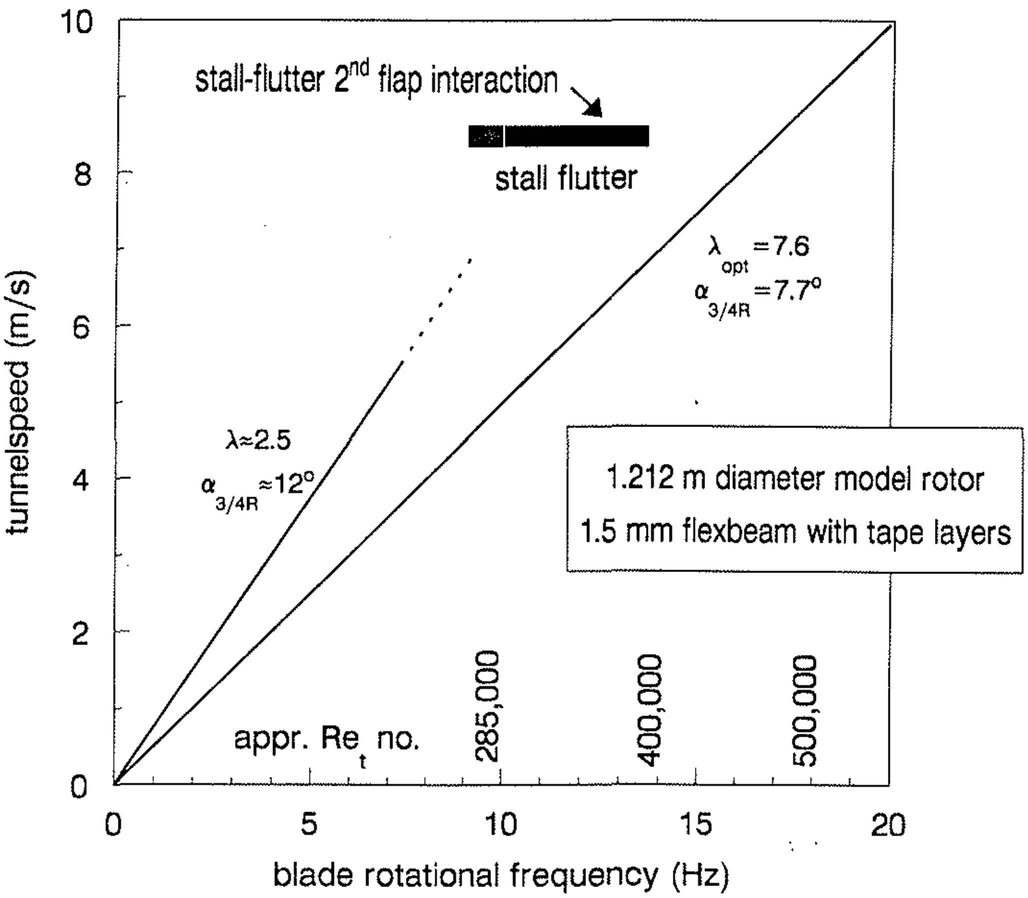

Fig. 2: Instability diagram denoting 2nd flap interaction range