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FLUTTER ANALYSIS OF TWIN TURBOPROP AIRCRAFT WITH TIP-TANKS

Jiri Cecrdle, Ph.D.*, Ondrej Vich*
*Czech Aerospace Research Centre (VZLU), Prague, Czech Republic;

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Abstract

This paper deals with aeroelastic (flutter) analysis of an aircraft with unconventional wing structure, which is specific by the installation of wing-tip tanks. In addition, the wing configuration without tip-tanks is also applicable at aircraft operation. The subjected aircraft is twin wing-mounted tractor turboprop commuter aircraft for 19 passengers, with a wingspan of 9.6 m and a maximal take-off weight of 7000 kg.
The paper is focused on the assessment of specific flutter issue, originating from the unconventional wing configuration. Further, another specific flutter issues related to elevator flutter and rudder flutter are described.

1 Introduction

Aircraft are required to have a reliability certificate including the flutter stability. Flutter analysis [1] [2] [3] must include all mass configurations in terms of fuel or payload, which are applicable at an aircraft operation. These configurations are given from the typical flight profiles, e.g. maximal flight distance profile, maximal payload profile, etc. Installation of tip-tanks significantly increases the number of applicable mass configurations. During the flight, the fuel is transmitted from the tip-tanks to the main tank, when enough space becomes available. The amount of fuel in the tip-tanks decreases while the fuel in the main tank increases; however, it must also take into account the fuel consumption because the fuel pumping process takes some time, during which the aircraft is burning fuel. The example of mass configurations for the maximal flight distance profile including tip-tanks is shown in figure 1.

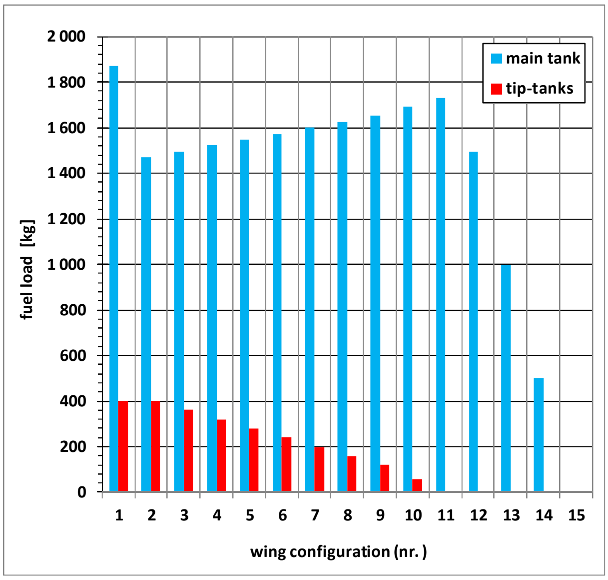

Fig.1. Mass configurations of fuel load including tip-tanks

Installation of tip-tanks causes significant variability in characteristics of the wing bending and torsional modes. Fuel load in the tip-tank represent large moment of inertia, even placed at the wing-tip, and therefore, frequencies of wing torsional modes rapidly increase as the wing-tip fuel load decrease. At the same time, frequencies of the wing bending modes are increasing as well; however, the rate of change is considerably lower. As a consequence, the crossing of frequencies of some bending and torsional modes inherently appears with the negative outcome to the wing bending - torsional flutter. This flutter is very sensitive to the wing modal characteristics.

The subjected aircraft is twin wing-mounted tractor turboprop commuter aircraft for 19 passengers, with a wingspan of 9.6 m and a maximal take-off weight of 7000 kg. The described wing flutter issue as well as another elevator flutter-related and rudder flutter-related issues are the subjects of the presented paper.

2 Flutter Analyses Background

Flutter analyses were performed using PK-based method [4] [5], in which, aerodynamic matrix is included into the stiffness matrix (real part) and into the damping matrix (imaginary part). The method generates directly total damping of the vibrating system for the selected velocities (true air speed). Flutter analyses were performed as non-matched analyses, i.e., aerodynamic matrices were generated for the reference Mach number (M_{REF}) for the selected values of reduced frequency (k). The velocity and Mach number values do not match, and therefore, the results have reference character. Such an approach is usually employed in the aeroelastic analysis to evaluate the rate of reserve in terms of the stability with respect to the specific (certification) velocity ($1.2*V_D$). Reference Mach number is usually $M_{REF} = M_D$. Results for velocities over the certification velocity ($1.2*V_D$) are just reference to evaluate the mentioned reserve. Analyzed flight altitudes (air densities) were set according to the V-H envelope. Structural damping was included using viscous model with the common value of g = 0.02.

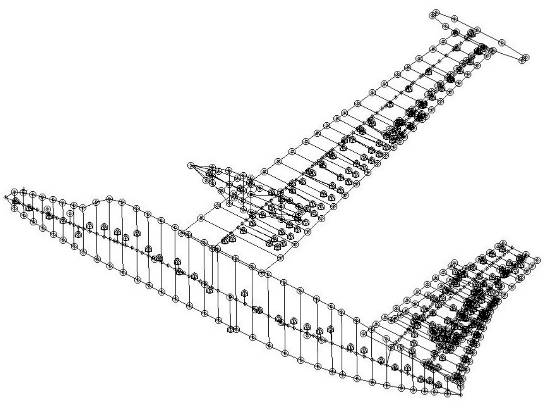

Fig.2. Structural model

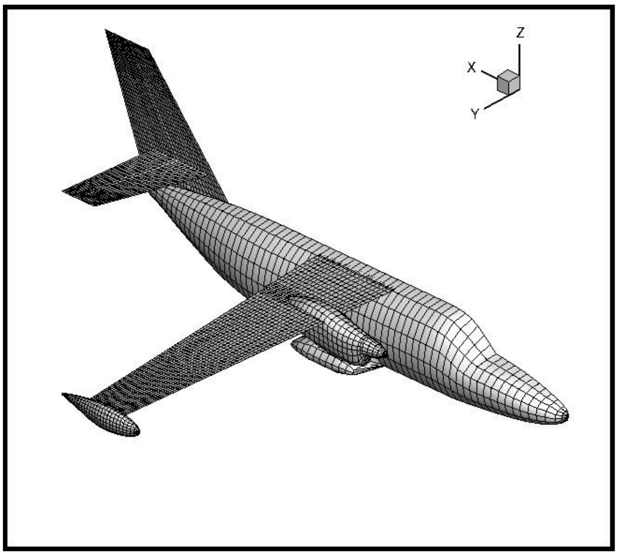

Fig.3. Aerodynamic model

Computational model for aeroelastic analyses was built as a dynamic stick model. Stiffness characteristics of structural parts were modelled using massless beam elements placed at the elastic axes of the particular structural parts. Stiffness characteristics of all structural parts (wing, fuselage, horizontal tail, vertical tail) including control surfaces (aileron, elevator, and rudder) and tabs (aileron tab, elevator tab, and rudder tab) were also modelled. Engine attachment stiffness as well as connections of structural parts was modelled using spring elements.

Inertia characteristics were modelled using concentrated masses with appropriate mass moments of inertia. Model also included various conditions, multi-point constrains, e.g., for the attachment of control surfaces, visualization, connections, etc.

Available configurations included fuel load, payload, control surface balance, etc. Model included half-span with the appropriate boundary condition (symmetric, antisymmetric) and half-values of mass and stiffness at the plane of symmetry. Structural model is shown in figure 2.

Aerodynamic model was prepared using a combination of panels (lifting surfaces) and Slender Bodies [4] (fuselage, nacelle, tip-tank).

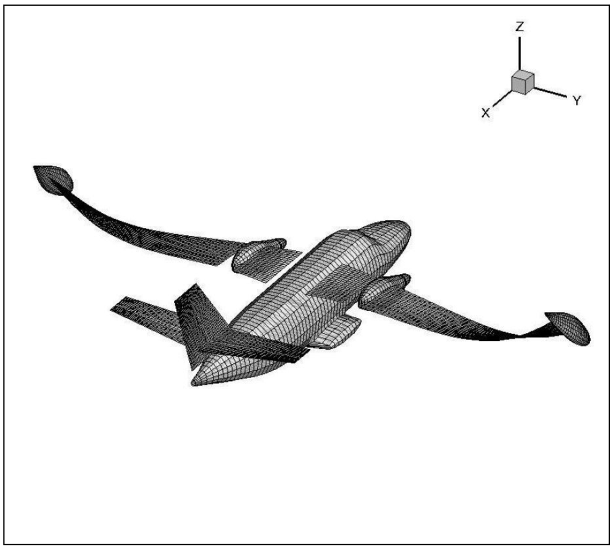

Fig.4. Wing bending – torsional flutter shape

Aerodynamic model was also half-span with the appropriate boundary condition. Interpolation between both models was realised using beam splines. Model included correction factors for the propeller slipstream using simple momentum theory. Further correction factors included correction for the control surface hinge moments and correction for the plane of symmetry. The aerodynamic grid is shown in figure 3.

Obviously, analyses were performed using either symmetric or antisymmetric modes. Flutter results included flutter critical states, i.e., flutter speed, flutter frequency, critical mode and contributing modes, flutter shape and V-g-f diagrams.

3 Wing Bending – Torsional Flutter

Two variants of model were included into the presented evaluation of the bending – torsional flutter. Both represent the latest version of the subjected aircraft in the different stages of development. The first variant represents early state in which structural parameters were set according to virtual model data without any relation to the prototype, while the second represent the late state, in which structural parameters were updated according to the prototype tests, in particular to the GVT (ground vibration test).

For the subjected aircraft, the major contributing modes of mentioned bending - torsional flutter type were 1st symmetric wing torsion (1.SWT) and 2nd symmetric wing bending (2.SWB). In addition, Symmetric engine pitch (SEP) vibration mode was also

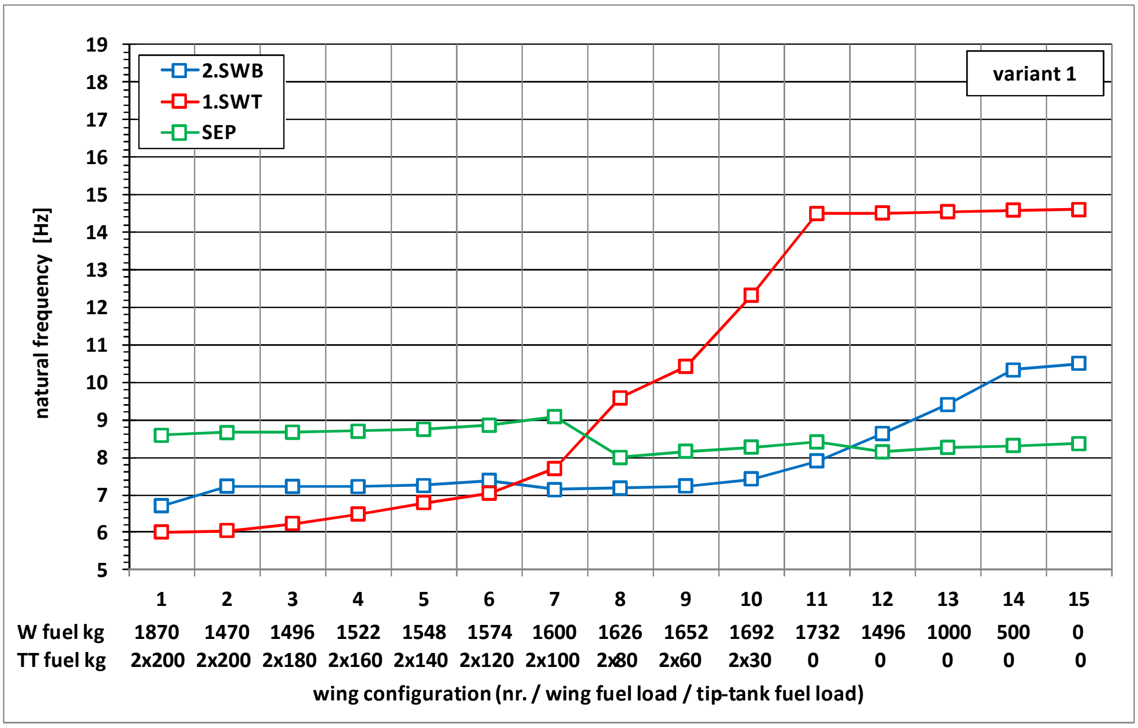

Fig.5. Wing natural frequencies (variant 1) vs. mass configuration

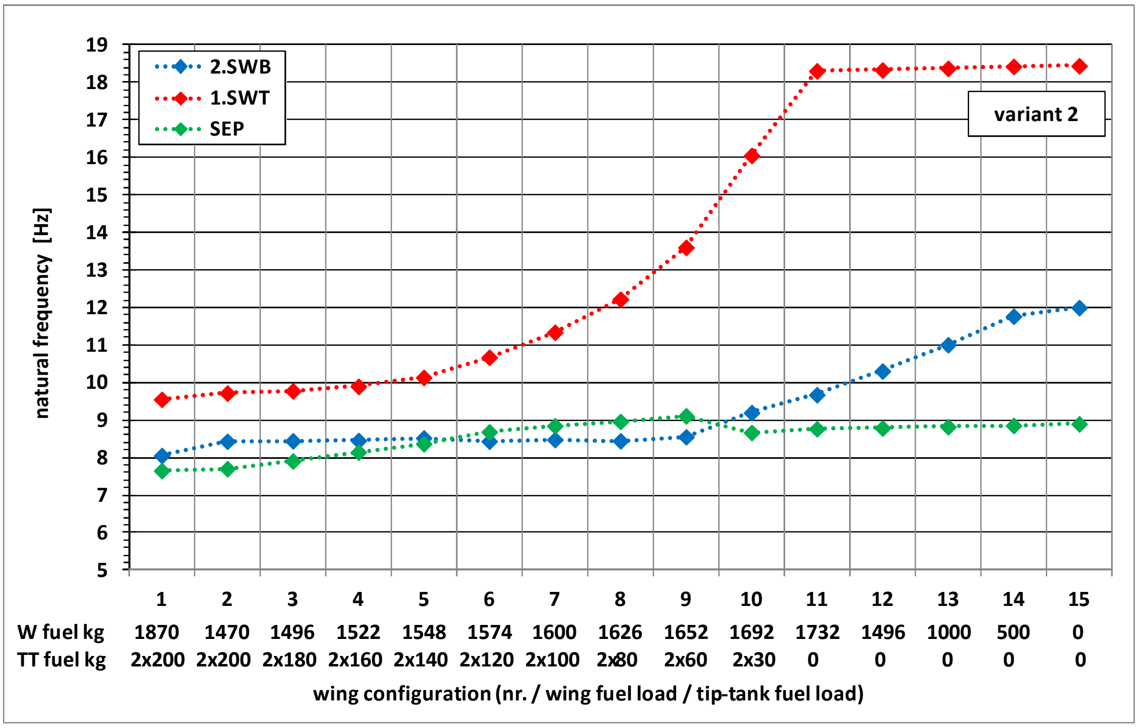

Fig.6. Wing natural frequencies (variant 2) vs. mass configuration

contributing to this flutter. Flutter shape is shown in figure 4.

Figures 5 and 6 shows natural frequencies of these modes for the mass configurations, representing the maximal flight distance flight profile with tip-tanks, for both variants 1 and 2. Configuration nr.1 represents the full fuel load, configurations 2 – 11 represent the fuel transmission and finally, configuration 12 – 15 represent the wing fuel load and empty tip-tanks. Frequency of the 1st symmetric wing torsion rapidly increases as long as the tip-tank fuel decrease (configurations 1 – 11) and remain at the same level for the zero tip-tank fuel (configurations 11 – 15). Contrary to that, frequency of the 2nd symmetric wing bending mode increase as long as the wing fuel decrease, i.e. within configurations 1 – 2 and 10 – 15 and remain at the same level during the fuel transmission (configurations 2 – 10).

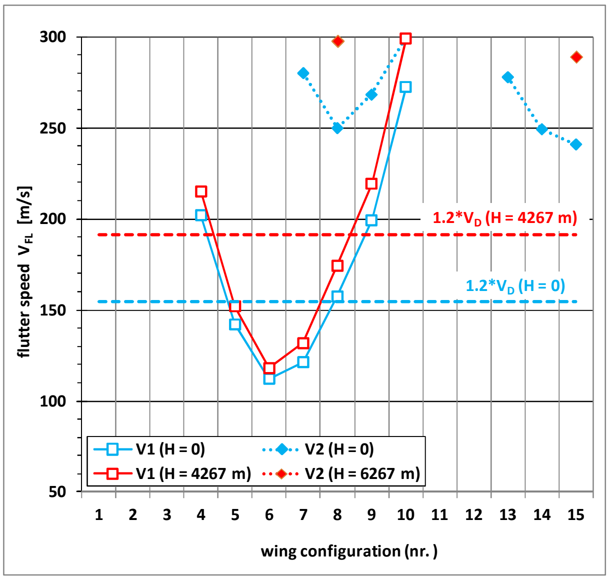

Fig.7. Wing bending – torsional flutter speed vs. mass configuration

Figure 5 shows the frequencies of variant 1. There is the frequency crossing of 1st symmetric wing torsion and 2nd symmetric wing bending modes around configurations 6 and 7. Contrary to that, in variant 2 (figure 6), the crossing was eliminated as the frequency of 1st symmetric wing torsion significantly increased.

Figure 7 shows the resulting flutter speeds at the altitudes of H = 0 and H = 4267 m (14 000 ft) for both variant 1 and variant 2. Considering variant 1, there is a flutter with the significant drop in the flutter speed. The lowest flutter speed was found for configuration nr. 6. Flutter speed is under the certification velocity (1.2*V_D), for configurations nr. 5 – 7 at H = 0

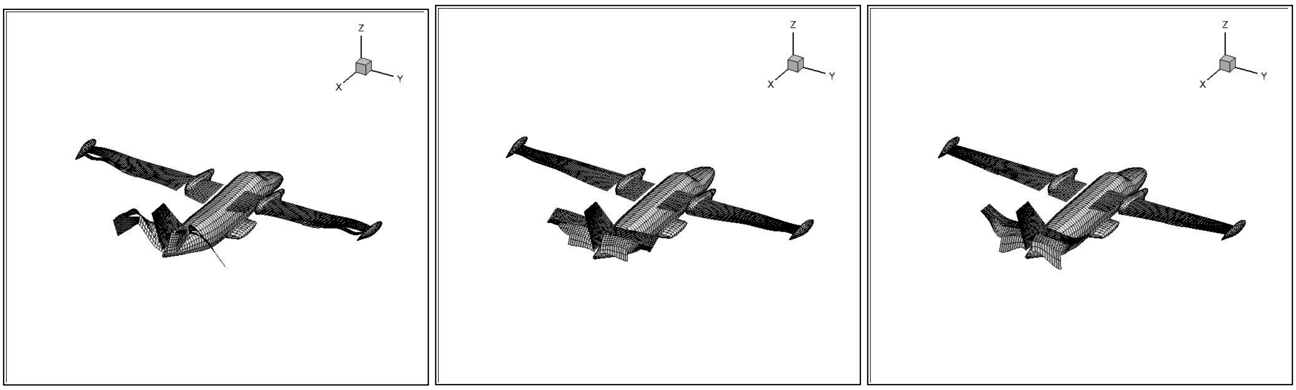

Fig.8. Examples of tailplane / elevator / elevator tab flutter shapes

and for configurations nr. 5 – 8 at H = 4267 m. Such a case would not be acceptable with respect to certification. Flutter frequency is ranging from 7.1 to 7.6 Hz.

Contrary to that, for variant 2, due to the increase in all frequencies, especially the one of 1st symmetric wing torsion, flutter speeds are much higher and well above the certification threshold. Also, flutter frequency increased to the range from 10.5 to 15.0 Hz. Thus, the certification problem of bending torsional flutter was eliminated.

4 Elevator Flutter

Elevator of the subjected aircraft was specific due to its large static unbalance (centre of gravity aft a hinge axis). In general, static unbalance makes a structure vulnerable to control surface flutter. In addition, static unbalance has usually negative effect on dynamic balance with respect to common modes of a surface [6]. Therefore, static unbalance is not generally recommended. Nevertheless, it is acceptable, provided no flutter appearance is properly justified.

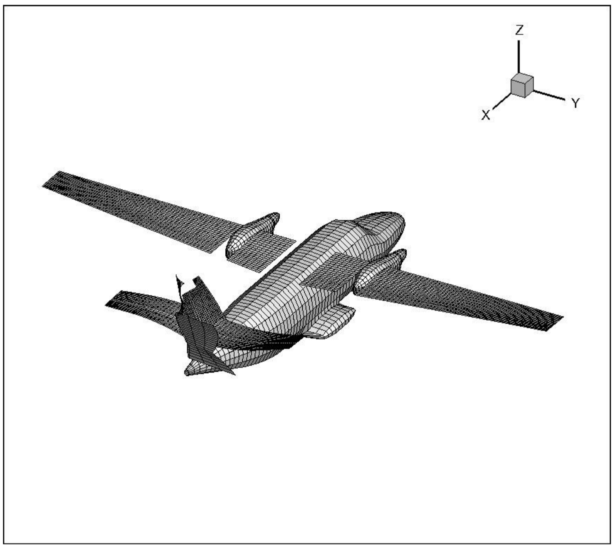

Fig.9. Rudder flutter shape

Elevator unbalance, which was as high as 4.5% of the elevator mean geometric chord, was adopted from the previous specification of the subjected aircraft. Although, the unbalanced elevator has been already in operation, flutter study was required anyway, at least due to the increase in certification speed of the subjected aircraft compare to the previous specification.

Several types of elevator flutter or elevator tab flutter (both symmetric and antisymmetric) were found; each of them caused by a specific combination of elevator and tailplane modes. Particular instabilities were appearing within a limited range of flight altitudes. The examples of symmetric elevator / tailplane flutter shapes are shown in figure 8.

Flutter study included nominal state and the variation of elevator parameters (flapping frequency, unbalance). The study evidenced no flutter inside the envelope of required stability considering the nominal state and the reasonable variation of structural parameters. Flutter states inside the certification envelope were just found for a very large elevator unbalance or for a very high elevator flapping frequencies. Thus, unbalanced elevator might have been applied on the subjected aircraft.

5 Rudder Flutter

Vertical tail and rudder of the subjected aircraft was, compare to the previous specification of the aircraft modified. Modification included increase in span, and mainly an increase in rudder horn balance surface in terms of both span and chord. Consequently, rudder mass-balance weights were modified as well. Removable weights to adjust rudder balance were placed at the leading edge of the horn balance.

There was found rudder flutter instability with the combination of rudder flapping and rudder torsional mode. Also, rudder tab flapping mode was contributing to this flutter issue. Flutter shape is shown in figure 9. The key factor was increase in mass moment of inertia of the upper rudder part due to the increase in mass-balance weight arm.

Considering the nominal (statically balanced) rudder, flutter speed was very close to the margin of required stability, but still above the certification threshold. However, any unbalance of rudder would push the flutter speed below the threshold. Moreover, rudder over-balance by increasing the removable weight placed at the horn balance leading edge had almost no effect on flutter speed. Therefore, the study of rudder dynamic balance with respect to node lines of appropriate modes was performed. The study evidenced small dynamic effect of the horn balance weight with respect to the flutter major mode.

After that, optional placement of mass-balance weight, which would be dynamically effective, was determined. The mass-balance weight placed here was capable to push the rudder flutter speed higher. Therefore, the removable mass-balance weight was moved to this new, rudder bottom-part, position. Figure 10 shows the flutter speed, projected into the V-H envelope for the various rudder balance choices. It illustrates the effect of the weight placement on flutter. Over-balance using the top

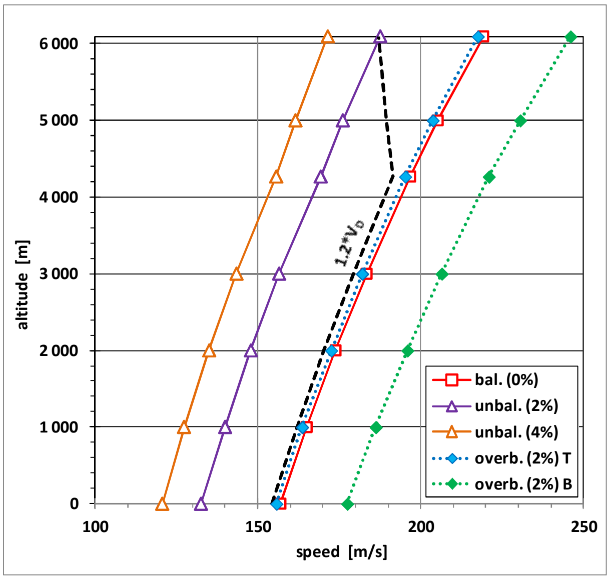

Fig.10. Rudder flutter speed in certification envelope

weight (T) has almost no effect on flutter while over-balance using the bottom weight (B) has significantly stabilising effect.

6 Conclusion

Presented paper deals with aeroelastic (flutter) analysis of twin wing-mounted tractor turboprop commuter aircraft for 19 passengers, which is specific by the wing structure with tip-tanks. The paper is focused on the assessment of specific flutter issues, which include bending – torsional flutter originating from the installation of tip-tanks, elevator flutter originating from elevator static unbalance and finally rudder flutter originating from small dynamic effectiveness of mass-balance weight. These flutter issues were assessed with respect to certification of the subjected aircraft.

7 Acknowledgement

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8 Contact Author Email Address

mailto: cecrdle@vzlu.cz

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