

# Radar Target Discrimination of Real Size Aircraft with Minor Structural Variations: Challenges and Solutions

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**Abstract**—A novel aspect independent resonance based radar target discrimination method has been developed in a previous work, and is found to be effective in discriminating canonical shape closely resembling objects with minor structural variations. The method utilizes the Radar Cross Section (RCS) of the unknown target to be identified and the distinction polynomial stored in the database (built from the dominant resonances of the known target). In this paper, the method is implemented successfully to discriminate two real size F5 aircraft with minor structural variations between them. This study involving real size targets poses some challenges that are overcome in this paper. The foremost challenge is the accurate computation of resonance range RCS of electrically large sized target considered ( $> 10\lambda$ ), which is computationally demanding. The second challenge is in selecting the dominant resonances (features) of the complex target useful for discrimination from a large set of resonances representing the target. The accuracy of the discrimination result is dictated by the accuracy with which the features of the targets are identified. This in turn is dependent on the accuracy with which RCS is determined. To achieve accurate results, the exact Computational Electromagnetic (CEM) method — the Method of Moments (MoM) is used for computing the RCS of real size aircraft. The procedure to choose an optimal number of dominant natural resonant frequencies (NRFs) from a pool of NRFs for real size complex target is presented in this paper. The discrimination quantifying function ‘Risk’ is shown to be effective in discriminating F5 aircraft — with and without missile attached underneath. The two targets have been successfully discriminated at all aspects, which is yet another challenge, establishing the aspect independent discrimination capability of the technique.

## 1. INTRODUCTION

In electronic warfare, an accurate and quick assessment of the enemy aircraft in real-time is indispensable. To know whether the enemy aircraft is engaging a missile is crucial to instantly initiate an appropriate counter measure/s. This demands a discrimination technique that is quick and sensitive to assessing minor structural variations in the target.

The resonance based discrimination of targets with structural variations is based on the well-known Singularity Expansion Method (SEM) formulation proposed by Baum [3]. SEM has given rise to a number of resonance based techniques such as E-pulse, K-pulse, and their modifications which are implemented in either the frequency or time domains.

The techniques that are proposed in literature are implemented mostly for discriminating canonical shapes such as wires, spheres, and cylinders. In [4–8], the discrimination has been implemented on wire targets. In [9], the extended E-pulse technique is applied to discriminate conducting spheres of different diameters. Toribio et al. [10] have implemented a modified scheme of E-pulse technique to discriminate sphere, cylinder, and square plate. However, in reality, a real target’s size and shape are large and complex. In other words, discriminating real size aircraft may pose newer challenges, which becomes

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evident only when the method is implemented. It is observed that very few papers deal with the discrimination of real aircraft. In [11], scaled models of MIG 27 and F4 are discriminated using the signatures algorithm. Rothwell et al. [12] have discriminated scaled models of Boeing 707 and F18 using the E-pulse technique. In spite of the scaled models used, the efficiency of any discrimination technique is still neither acceptable nor implied until it has been successfully implemented on real size targets. Therefore, the techniques have to be tested for real size objects to ascertain their efficiency.

The literature review reveals the sparsity in applying the discrimination technique to real large size complex shaped objects. The E-pulse discrimination technique has been implemented on real size aircraft in [13], wherein the MiG-29 aircraft with and without stores are discriminated.

The foremost challenge while studying real large size complex targets is in computing the RCS accurately. It is easy to determine the RCS of canonical shape objects using either analytical or numerical methods. But in the case of complex shaped targets, there are no straight forward analytical techniques which can be used to determine the scattered fields. Although the experimental measurement of the target's response is the exact way to obtain the target's response, building the actual or scaled models of the targets and then carrying out measurements in anechoic chambers or in flight incurs prohibitive costs and turnaround time. The only other viable means is to resort to Computational Electromagnetic (CEM) techniques. The algorithms such as Method of Moments (MoM) are theoretically capable of handling objects of any characteristic dimension, but the computer resources (time and memory) available to run the algorithm dictate the limit on the size of the object.

Another important consideration for successful discrimination of targets is identifying the dominant natural resonant frequencies that represent the target accurately. For simple objects like wires and spheres, the resonances are few in number and can be computed analytically or extracted from the RCS using pole extraction techniques like Matrix Pencil of Function (MPoF) and Vector Fitting (VF) [14, 15]. The electromagnetic response of a complex target in the resonance region contains a large number of resonances. This is expected as each curvature, joint, fin, etc. of the target contributes to different path differences to the surface travelling wave that contributes to the formation of a complex return signal. Therefore, using analytical methods for determining the poles is difficult, and pole extraction techniques only have to be used. Pole extraction methods are inverse methods, and they tend to generate many spurious poles. Due to the complex shape of the target and complex nature of the return signal, it is difficult to tag a particular pole (resonance) as that generated from a particular part of the aircraft and weed out the spurious poles. Thus accurate identification of the true or dominant poles of complex targets is another challenge.

A target discrimination algorithm has been proposed by the authors in [1, 2], to discriminate targets that closely resemble in shape and have been successfully implemented on canonical and complex targets of small electrical sizes. The same algorithm is used in this study to discriminate real size electrically large, F5 military aircraft with missiles attached to it underneath.

The MoM is employed to compute the resonance range frequency response of real size F5 aircraft accurately.

The Vector Fitting method (VF) is applied to extract the poles from the response [15]. The order of the transfer function derived for complex objects is observed to be large ( $> 20$ ). For the proper identification of the true poles, the power contribution criterion has been proposed.

In Section 2, the discrimination method is presented. The RCS computation of the aircraft and identifying the dominant poles of the targets are presented in Section 3. The results and discussions of discriminating an F5 aircraft and an F5 with missile are presented in Section 4 followed by the conclusions in Section 5.

## 2. TARGET DISCRIMINATION METHOD

The resonance based discrimination method developed in [1, 2] is implemented to discriminate between the F5 aircraft and the F5 aircraft with two missiles attached underneath. In this paper, discrimination of (F5 and F5 + missile) means that F5 is considered as the known database target, and F5 + missile is the unknown target which is compared with the database target F5. Likewise, discrimination of (F5 + missile and F5) means that F5 + missile is considered as the known database target, and F5 is the unknown target which is compared with the database target F5 + missile. The amount of

discrimination is quantified by a value called 'Risk'. For the sake of completeness, the definition of Risk [16] is presented here.

The distinction polynomial  $D(j\omega)$  is built using the dominant NRFs  $a_n$  of known target and is defined as

$$D(j\omega) = \prod_n (s - a_n) \quad (1)$$

The Risk factor is defined as

$$R_{td} = \int_{\omega_a}^{\omega_b} \left\{ \frac{d^3}{d\omega^3} [|D_d(j\omega)|^2 \cdot A_t(\omega)] \right\}^2 d\omega \quad (2)$$

Here,  $|D_d(j\omega)|^2$  is the distinction polynomial of known target, and  $A_t(\omega)$  is the RCS of unknown target. The term  $(\omega_a - \omega_b)$  is the resonance range of frequencies for which the RCS of the unknown target is obtained. Further, a discrimination quantifying number 'Risk' is defined as-

$$\text{Risk} = \frac{R_{td}}{R_{dd}} \quad (3)$$

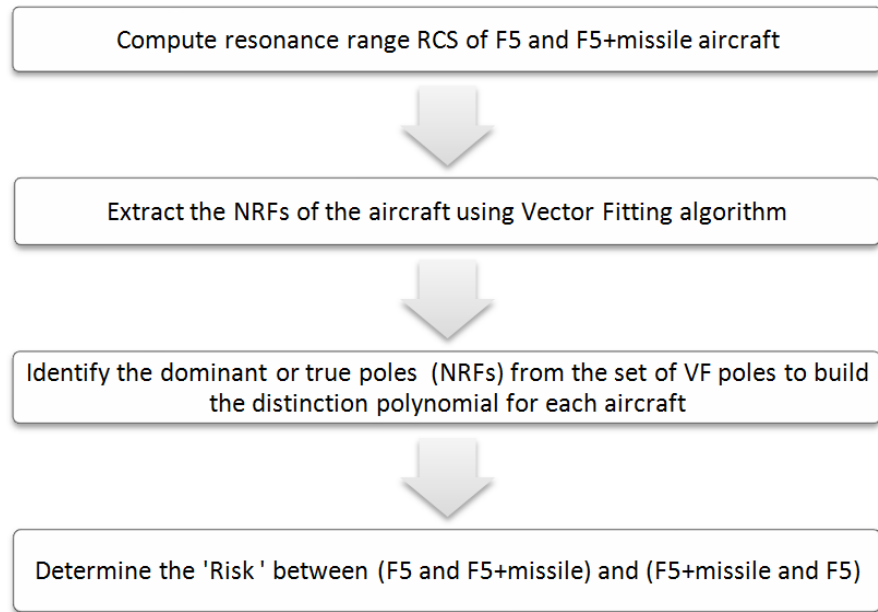
$R_{dd}$  is the risk factor between the database target and itself.

Risk in dB is given by

$$\text{Risk(dB)} = 10 \log(R_{td}) - 10 \log(R_{dd}) \quad (4)$$

For a matching target, the Risk in dB is close to zero, whereas for differing targets, the difference is large in magnitude.

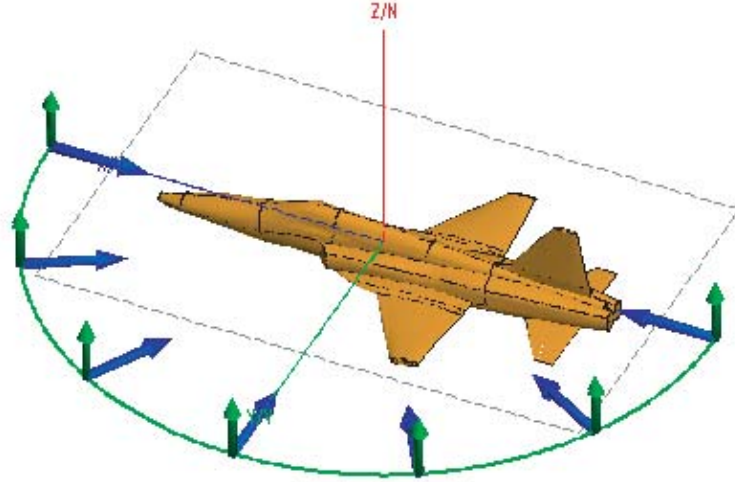
The steps involved in the discrimination of F5 and F5 + missile aircraft are briefly summarized in Fig. 1.



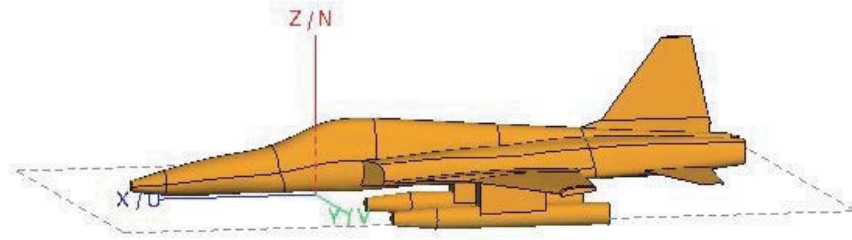
**Figure 1.** Discrimination steps.

### 3. COMPUTATION OF RESONANCE RANGE RCS OF F5 AIRCRAFT AND IDENTIFYING ITS DOMINANT POLES

The F5 fighter aircraft model used in this study is shown in Fig. 2. The model was obtained from the FEKO [17] database. The aircraft has fuselage of length 14 m, wing span of 8 m, and height equal to



**Figure 2.** F5 aircraft model.



**Figure 3.** F5 + missile aircraft model.

2 m. To this aircraft, two metallic missiles of length 5 m are attached under the wings which form the aircraft F5 + missile (the inclusion of the missiles introduces minor structural variation compared to F5 aircraft). The F5 + missile aircraft model is shown in Fig. 3.

### 3.1. Computation of RCS of F5 and F5 + Missile Aircraft

The Method of Moments is an exact method, which is best suited for accurate RCS computation in the resonance range of targets. The MoM, can generally handle the objects of electrical sizes up to  $25\lambda$  [18]. The MoM solver available in FEKO (v7.5) is used to compute the RCS of the aircraft.

The modelling and simulation settings of both F5 and F5 + missile aircraft are identical as they have same characteristic dimensions. The summaries of the two aircraft dimensions and simulation settings are provided in Table 1.

Considering the characteristic length of the aircraft to be varied between maximum of 14 m and a minimum of 0.6 m that contribute to the resonances, the frequency range for computing the RCS is fixed to be 1 MHz to 500 MHz to include the  $\lambda/2$  frequencies. At the highest frequency, electrical length of F5 aircraft ( $23\lambda$ ) approaches the upper limit of MoM. As the electrical size of the object becomes large, the number of meshes generated is also large as the mesh discretization is frequency dependent. The MoM solver discretizes the surface of the scatterer at the highest frequency and constructs 12 meshes per wavelength of the structure with the standard setting (FEKO standard mesh setting (v7.5): 12 meshes per wavelength at the highest frequency). Computing the RCS at the lower side of the frequency range, with meshing done at the highest frequency, resulted in huge number of unknowns (in millions) to be determined and posed computational constraints.

Due to the computational constraint, it was proposed to divide the frequency range into three parts — (1–150) MHz, (151–300) MHz, and (301–450) MHz. The RCS was computed at 32 linearly spaced points in steps of 4.80645 MHz in each range and a total of 96 discrete frequency steps for the

**Table 1.** F5 and F5 + missile aircraft: Dimensions and Simulation settings.

| Parameter                                                          | Dimensions/settings                                                                          |
|--------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
| <b>F5 Aircraft Dimensions:</b>                                     |                                                                                              |
| Length                                                             | 14 m                                                                                         |
| Wing span                                                          | 8 m                                                                                          |
| Height                                                             | 2 m                                                                                          |
| <b>Missile Dimensions:</b>                                         |                                                                                              |
| Length (cylinder + cone)                                           | 5 m                                                                                          |
| Diameter of cylinder, base of cone                                 | 0.5 m                                                                                        |
| Height of cone                                                     | 1 m                                                                                          |
| <b>Electrical size of aircraft (<math>L/\lambda_{\min}</math>)</b> | $21\lambda$ at 450 MHz                                                                       |
| Frequency range                                                    | 1 MHz to 450 MHz                                                                             |
| Solution method                                                    | Method of Moments                                                                            |
| Incident wave                                                      | Plane wave linearly polarized of 1 V/m magnitude                                             |
| Aspects at which monostatic RCS are computed                       | $0^\circ$ , $30^\circ$ , $60^\circ$ , $90^\circ$ , $120^\circ$ , $150^\circ$ and $180^\circ$ |

complete range. In each range, the aircraft was discretized with respect to the maximum frequency in that range. This permitted accurate computation of RCS with lower demands on memory and time. The monostatic RCS response was computed at seven aspect angles ranging from the nose-on to tail-on at  $\theta = 0^\circ$ ;  $\phi = [0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ \text{ and } 180^\circ]$  for both the aircraft.

The entire simulation was carried out on a system with 16 Intel Xeon®processors, 2.30 GHz, 126 GiB memory. The simulations were run on a single processor with 12 cores. The details of the number of unknowns and the memory and time requirements for computing the RCS of F5 aircraft using MoM are presented in Table 2.

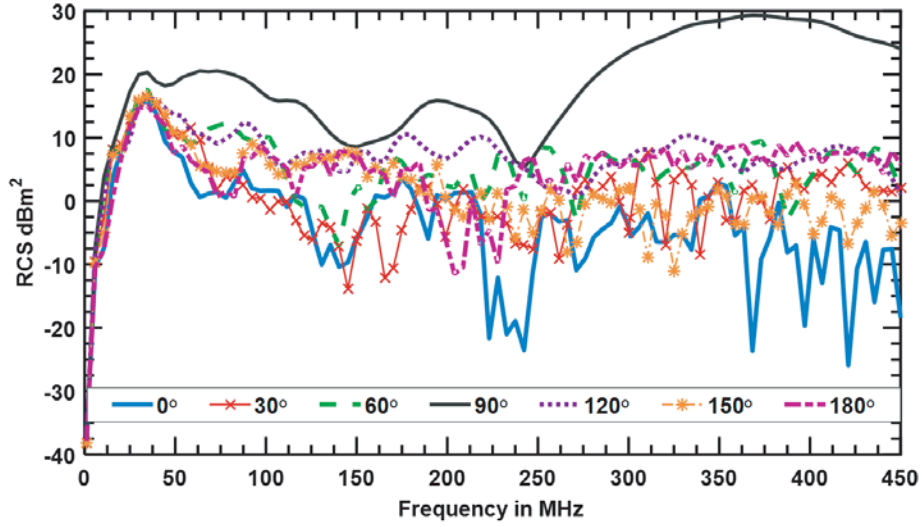
**Table 2.** Computational cost in simulating RCS of F5 aircraft using MoM.

| Frequency Range MHz | No. of meshes | No. of unknowns | CPU time in hours | Peak memory GB |
|---------------------|---------------|-----------------|-------------------|----------------|
| 1–150               | 25178         | 37751           | 72.193            | 10.796         |
| 151–300             | 42876         | 64290           | 260.582           | 31.096         |
| 301–450             | 70659         | 105974          | 878.096           | 84.172         |

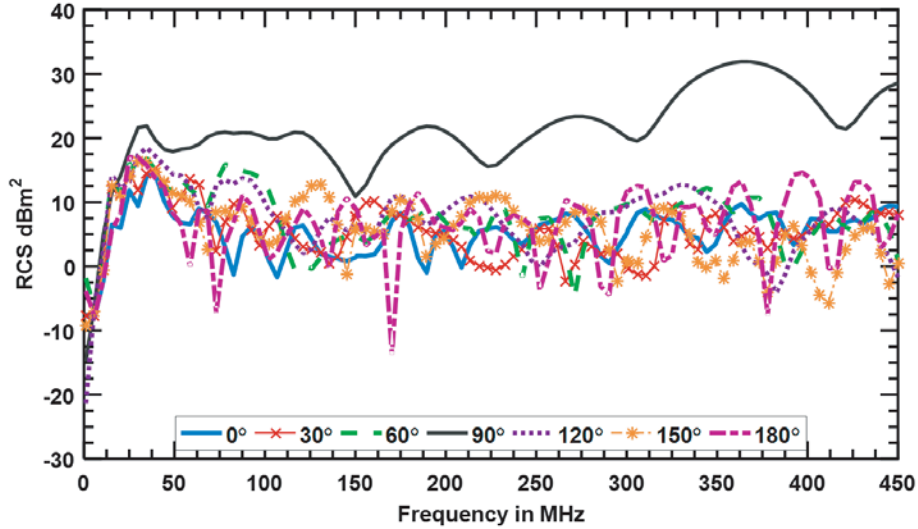
The CPU time in each frequency range includes computation of RCS at all 7 viewing angles. From Table 2, it may be observed that a total of 1210.871 hours (50 days approx.) of CPU time was required to compute the RCS of F5 aircraft at 96 discrete steps and at all 7 aspects. Similar time and memory were required for computing RCS of F5 + missile aircraft. The RCS responses of F5 and F5 + missile are shown in Figs. 4 and 5, respectively.

### 3.2. Identifying the Dominant Resonances of the Aircraft

It is essential for aspect independent discrimination that all of the dominant poles (NRFs) of the target are included in the distinction polynomial which forms the database for the target. The NRFs are aspect independent, but their corresponding residues are aspect dependent. Due to this, some of the dominant resonances of the target are not energised sufficiently at a particular aspect, but they are



**Figure 4.** RCS response of F5 aircraft.



**Figure 5.** RCS response of F5 + missile aircraft.

important in building the database polynomial. In order to completely determine the true NRFs of F5 aircraft, the EM responses at more aspect angles ranging from the nose-on direction to the tail-on direction are considered. This ensures that all of the dominant poles of the target are determined. The greater the complexity (shape variations) of the object is, the higher the order of the transfer function representing the complex object is. Typically, the order was found to be  $> 20$  for the complex objects, and it may vary slightly for the same target at different aspects depending on the poles that are excited. The poles of the same aircraft at different aspects, when being pooled together, are found generally dispersed, but few clusters of poles are noticed. Selecting the dominant poles from such a collection of poles by applying the criteria proposed in [1] was found to be inadequate in this case of real large size complex target. In order to choose the dominant poles that succinctly represent the target, the power contribution of each probable pole to the total power contributed by the complex LHP poles to the response was considered.

The process of determining the dominant poles with the power criterion is described below.

### 3.3. Power Contribution Criteria for Identifying the True Poles of Complex Objects

To select the most dominant poles that represent the structure of the target, the power contribution of each pole to the response is assessed [2].

The steps to choose dominant poles are summarized here —

- Determine the power contribution of each eligible complex VF pole (LHP-pole) to the response of the target.
- Determine the total power contribution of all the selected LHP VF poles.
- Choose only those LHP VF poles that contribute more than 10% to the total power for identifying it as a dominant pole of the target.

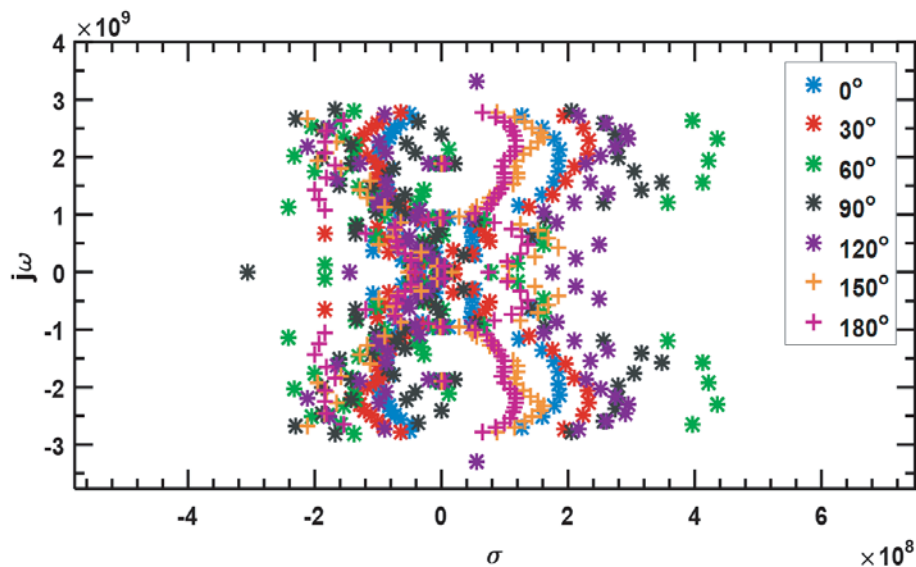
$$P_{dominant} \geq 0.1P_{Total} \quad (5)$$

where  $P_{Total}$  is the total power contribution of all the LHP VF poles to the response, and  $P_{dominant}$  is the power contribution of a particular dominant pole which is more than 10% of the total power.

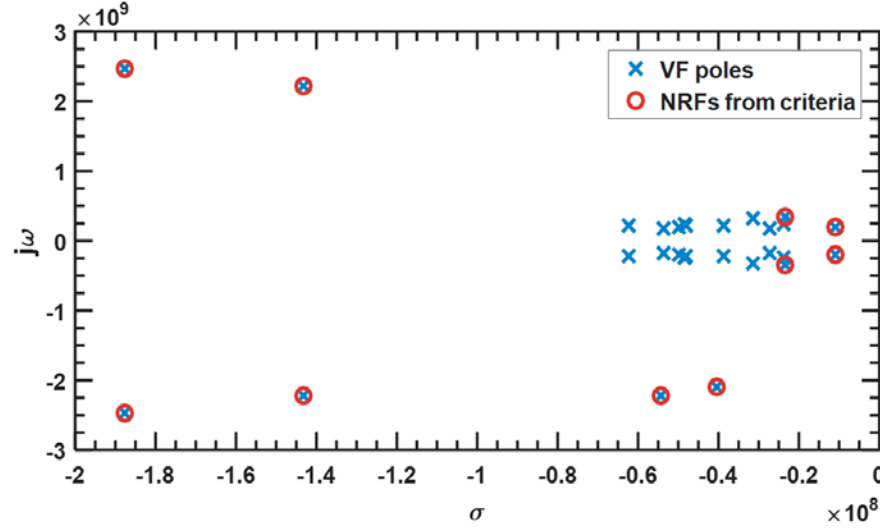
## 4. RESULTS AND DISCUSSION

### 4.1. Dominant NRFs of F5 and F5 + Missile Aircraft

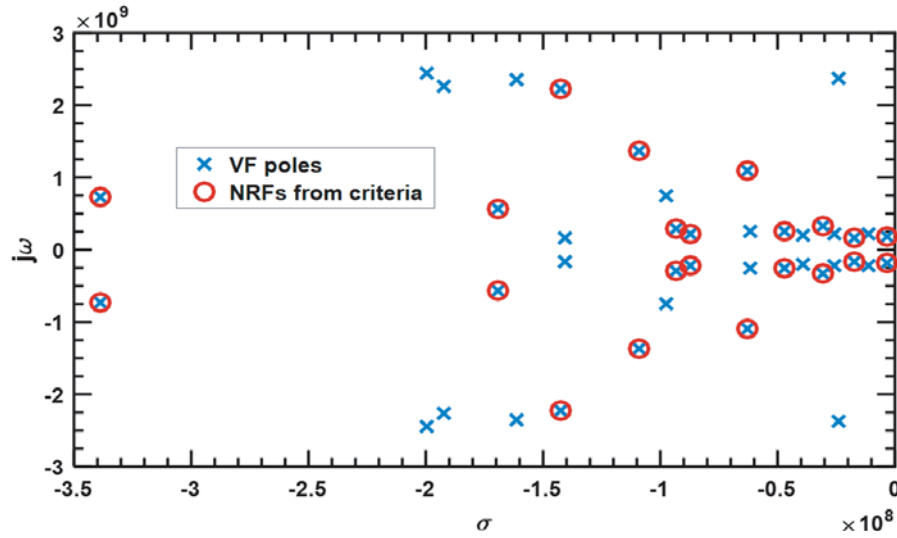
As can be visualized in the RCS plots of F5 aircraft and its variant, F5 + missile (Figs. 4 and 5), the response contains numerous resonances due to the complex shape with a number of scattering centres. The poles of the aircraft were extracted from the frequency response using the Vector Fitting method. The order of the function at each aspect was set by determining the value which produced least RMSE. In the case of these two real large size aircraft, the order of the function  $N$  was seen to vary from 86 to 98 which is very large. For illustration, the complete VF poles for F5 aircraft at different aspects is shown in Fig. 6. The RMSE obtained was of the order  $1E-4$  generally. To identify the dominant poles of the signals, the power contribution of each LHP pole was assessed at each aspect separately. The final dominant poles were identified from the union of power contributing poles determined at each aspect and applying the other criteria. The dominant NRFs of F5 and F5 + missile aircraft are given in Figs. 7 and 8. It is observed that many of VF poles have been discarded by applying the power contribution criteria. At the same time, the dominant poles have been identified succinctly. The high frequency poles appearing in both the aircraft pole sets match closely. It is interesting to note that these poles



**Figure 6.** VF poles of F5 aircraft at different aspect angles.



**Figure 7.** Dominant poles of F5 aircraft.



**Figure 8.** Dominant poles of F5 + missile aircraft.

are actually due to smaller parts of the aircraft that are commonly present in both the aircraft. The pole frequency confirming to the dimension of the missiles ( $L = 5$  m) is  $(-3.251E6 \pm 1.770E8i)$  that appears only in the pole set of F5 + missile aircraft as a low order frequency. This observation explains the need to consider low as well as high frequencies for the discrimination purposes.

#### 4.2. Discrimination of F5 and F5 + Missile Aircraft

The discriminating quantity Risk that measures the amount of dissimilarity between two compared targets was determined using the dominant NRFs determined in Subsection 4.1. The discrimination results are presented in Table 3. In the table, (F5 and F5 + missile) indicates that F5 is the database target, and F5 + missile is the unknown target. Similarly, (F5 + missile and F5) indicates that F5 + missile is the database target, and F5 is unknown. In both the cases of discriminating F5 aircraft (database) against F5 + missile (unknown) or vice versa, the Risk values obtained are satisfactory with more than 2 dB at all aspects. This demonstrates the aspect independent capability of the discrimination technique to distinguish real large size aircrafts with minor structural variations.

**Table 3.** Discrimination of F5 and F5 + missile.

| Aspect angle<br>in degrees | Risk in dB            |                       |
|----------------------------|-----------------------|-----------------------|
|                            | (F5 and F5 + missile) | (F5 + missile and F5) |
| 0                          | 43.9966               | −43.6192              |
| 30                         | 12.7206               | −12.6819              |
| 60                         | −2.5086               | 2.5895                |
| 90                         | 4.6158                | −4.6307               |
| 120                        | −9.9505               | 9.9739                |
| 150                        | 8.0241                | −8.0107               |
| 180                        | 4.8259                | −4.7183               |

## 5. CONCLUSIONS

The main focus of this paper is to implement the resonance based discrimination technique to distinguish real large size complex targets that are similar in size and shape but vary structurally with minor variations. The RCS of the F5 and F5 + missile aircraft have been accurately computed using MoM in spite of the computational constraints. Nevertheless, other computational techniques such as Finite difference Time Domain (FDTD) may also be employed. A comparative work on implementing the discrimination technique to some canonical shaped objects by extracting the resonances from FDTD's time domain responses and MoM's frequency domain responses have shown the advantage of adopting a hybrid approach to reduce the computational cost [19].

In order to tackle the overwhelming number of poles generated for the complex aircraft, the pole selection criteria has been refined by including the step to assess the power contribution of each pole to the RCS response to identify the dominant poles. This criterion is found to be efficient in weeding out the spurious as well as less dominant poles. The criterion also enables us to limit the number of true poles selected to represent the database target.

Discrimination of real size aircraft at various aspects considered yields a Risk of  $> 2$  dB which is a substantial quantity to ascertain the dissimilarity between the compared targets. The need for including both the low frequency poles as well as the high frequency poles for proper discrimination is emphasized in this study.

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